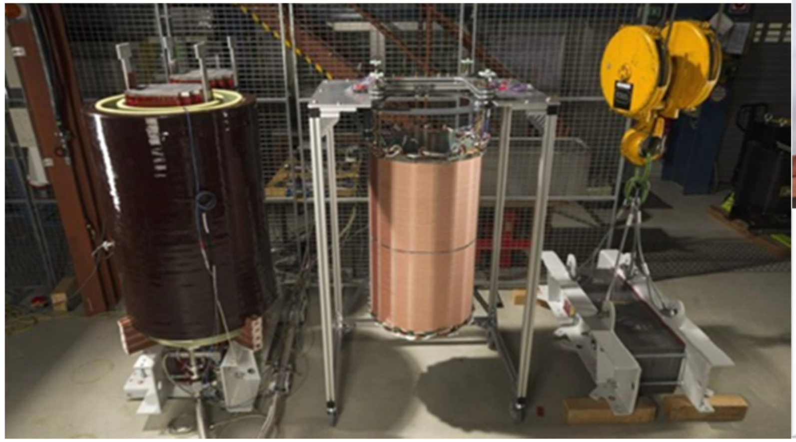
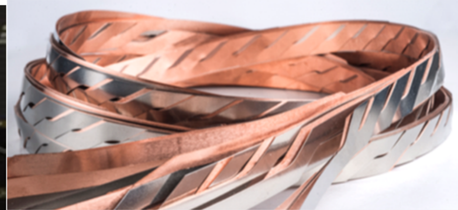
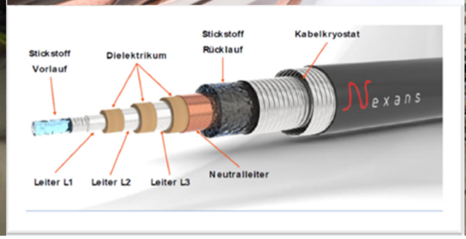
2019 European Cryogenics Days
7th.-8th. Oct. Lund (Sweden) – Medicon Village

Karlsruher Institut für Technologie

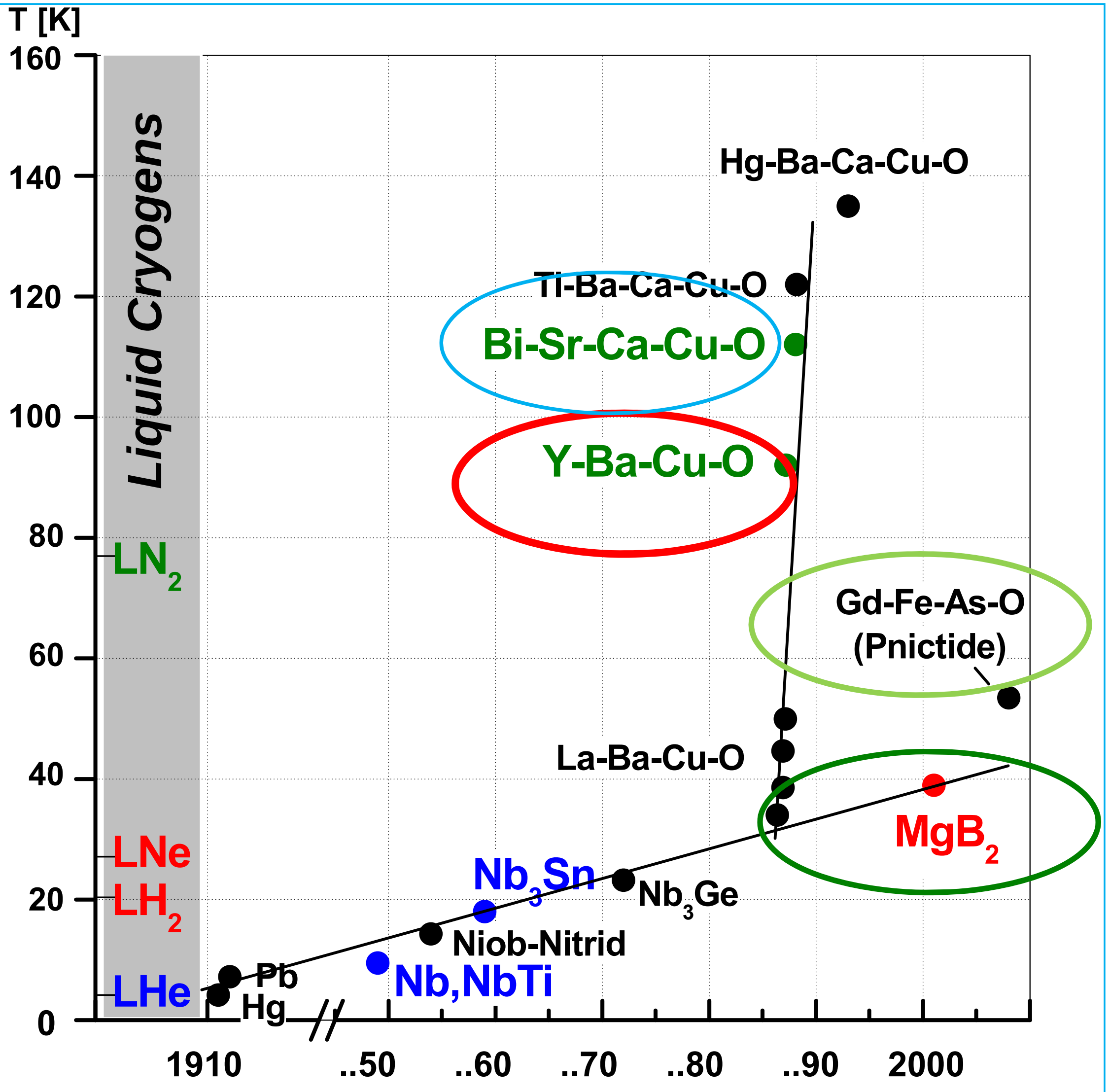





HTS – transformer, Low AC loss Roebel-cable, Ampacity power cable, Smartcoil current limiter, Ecoswing wind energy device

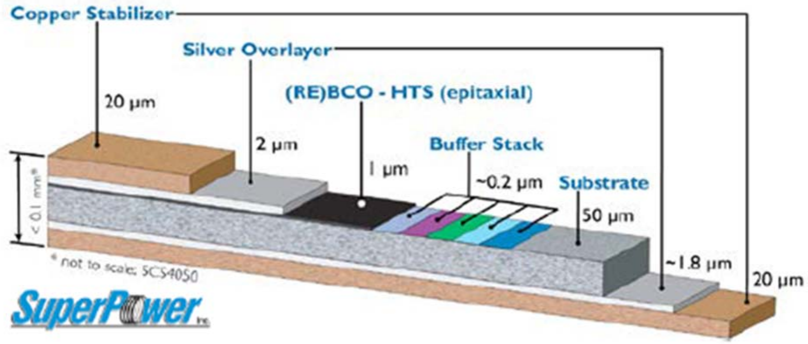
Overwiew on HTS projects and applications worldwide

Wilfried Goldacker, Mathias Noe
Karlsruhe Institute of Technology – Institute for Technical Physics
Hermann-von-Helmholtz-Platz 1
76344 Eggenstein-Leopoldshafen
Germany
Email: wilfried.goldacker@kit.edu

The different classes of HTS superconductors



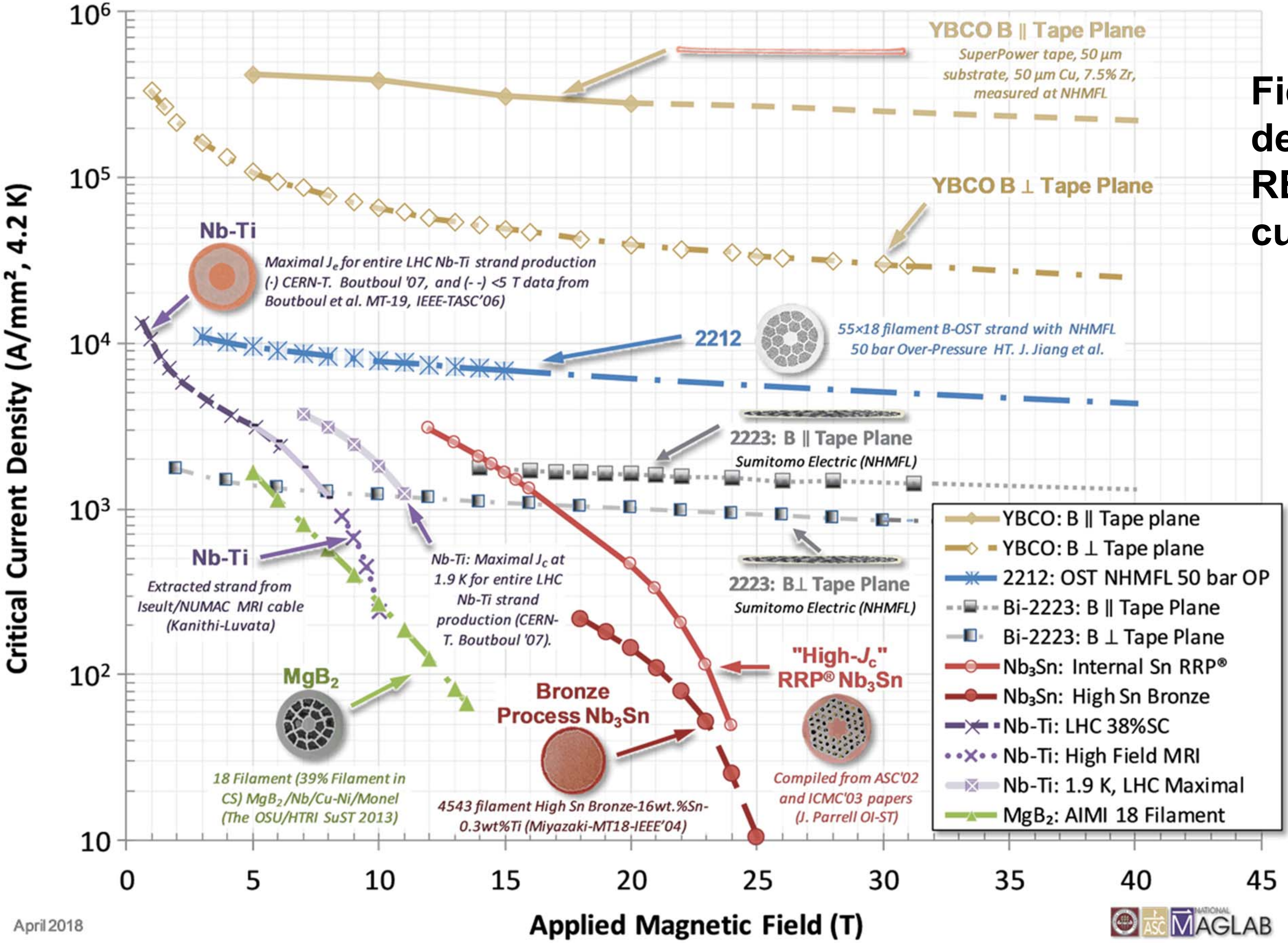
CC principle of architecture



- REBCO Coated Conductors are the working horse today
- BSCCO(2223) HTS is the past, BSCCO(2212) high pressure treated candidate for high fields
- Sophisticated preparation, high potential, next generation ?
- MgB_2 has niche applications !
- Enhanced pinning in Nb_3Sn with dispersed internal oxides is a new chance for higher fields !!!

Survey: Non-Cu critical current capacity

https://fs.magnet.fsu.edu/~lee/plot/plot.htm

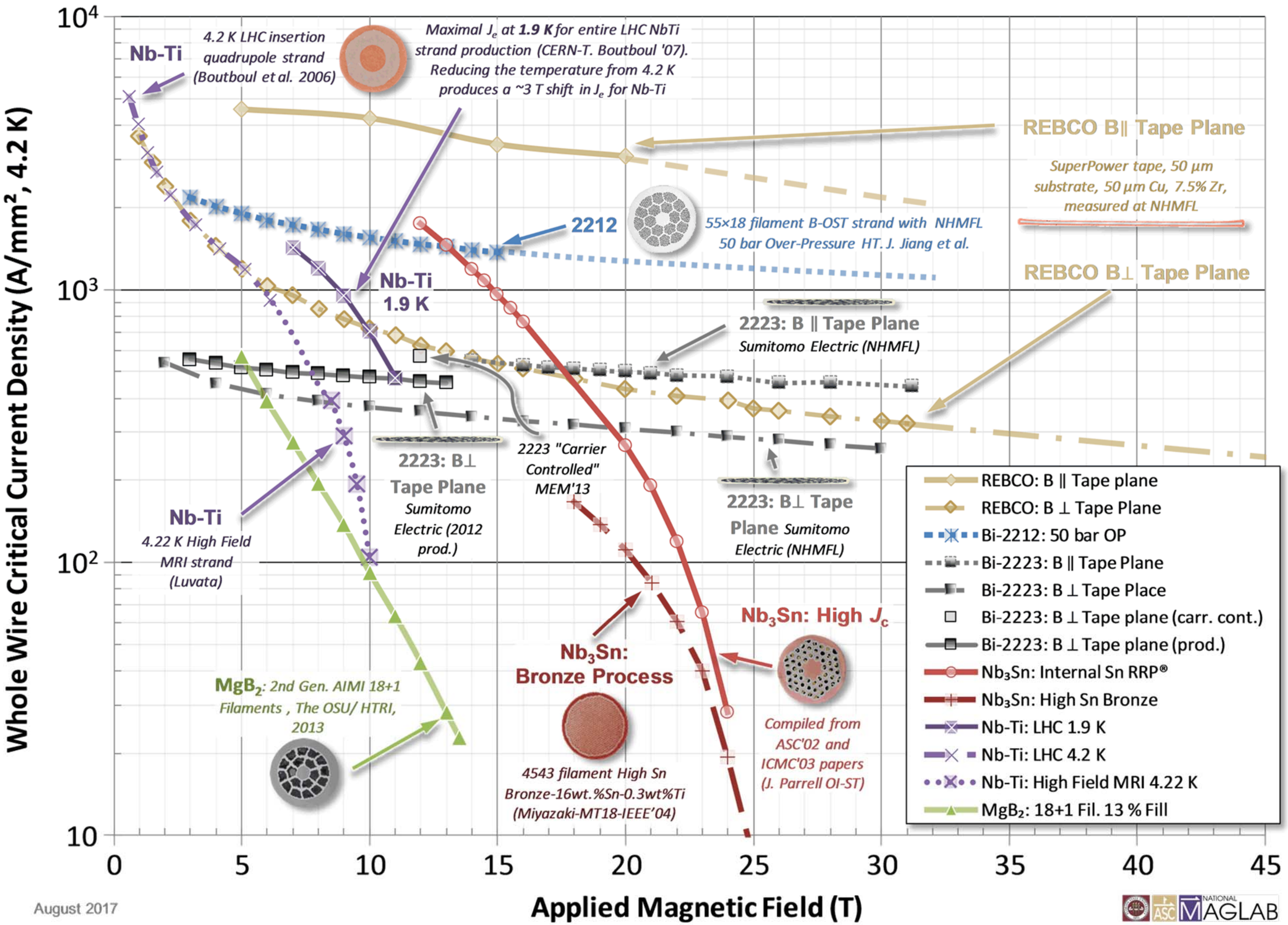


Field orientation dependency of REBCO critical current

P.Lee diagrams Florida State University/ NHFML USA

Survey whole wire critical current capacity

https://fs.magnet.fsu.edu/~lee/plot/plot.htm



Filling factor = content of supercon-ductor is important

Quite low for REBCO tape !

Efforts to reduce substrate

P.Lee diagrams Florida State University/ NHFML USA

Coated Conductor Manufacturers

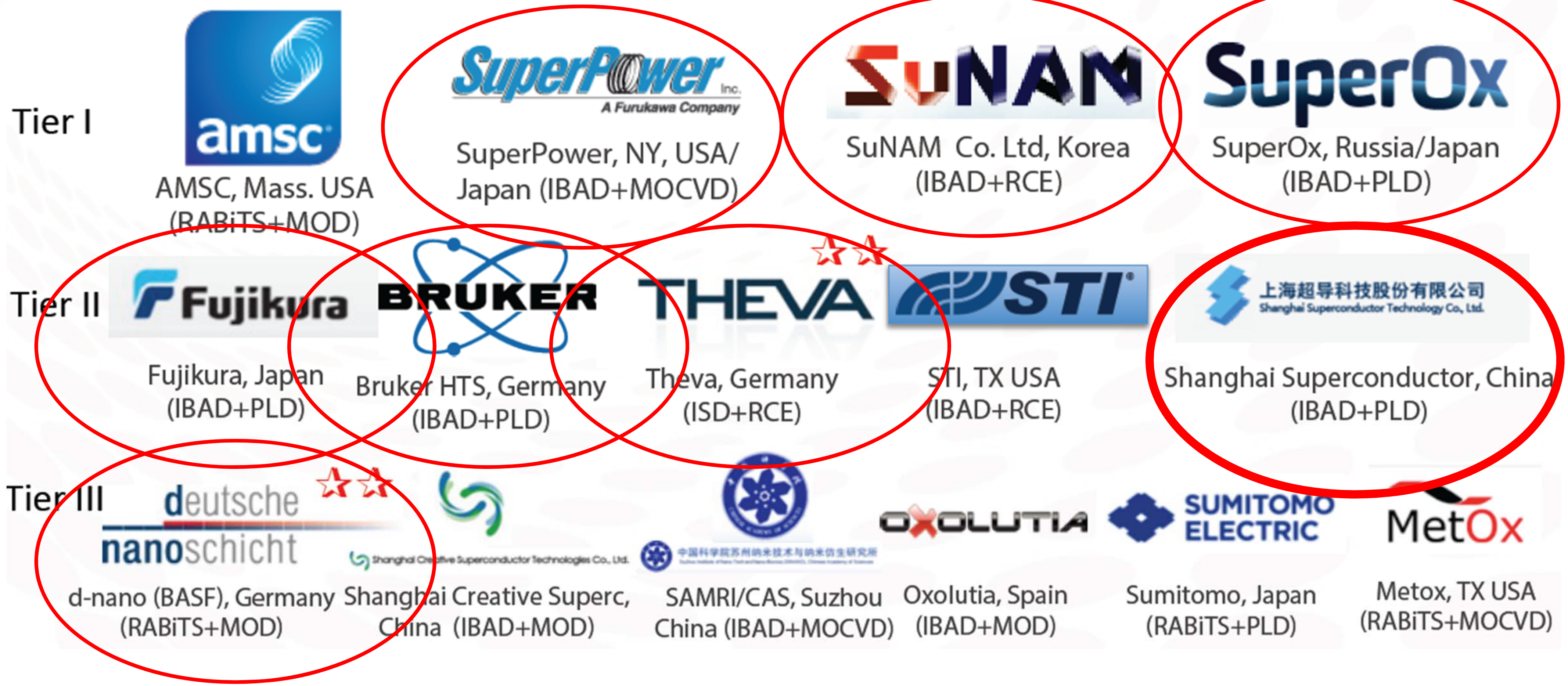


Figure. Vladimir Matias, iBeam, CCA-2016

Focus of companies:

Bruker: Magnet applications
THEVA: Energy & all applications
SuperPower: more 77 K applications

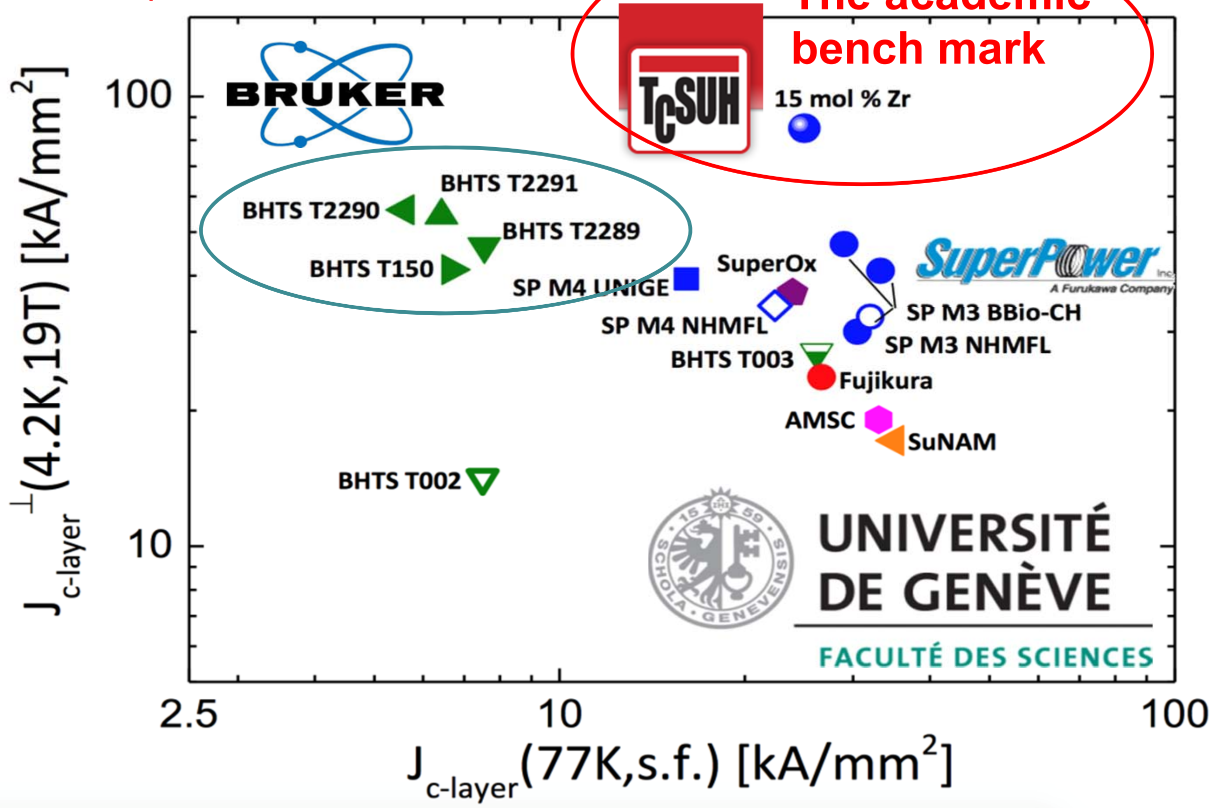
D-NANO: Cheap CSD CC-route
SSC: All applications
SuperOx: PLD + all applications
SuNAM: High current & magnets

Transport I_c of industrial CC materials 4.2 K / 77 K

- Investigation of Bruker, SuperOx, SuNAM, THEVA, SuperPower, Fujikura, AMSC - CC
- Evaluation criteria: Current capacity at 4.2 K and 77 K,
- Results were assembled during EU-project Eucard2 (CERN)

Status early 2016

Master plot (C. Senatore, U. Geneva)

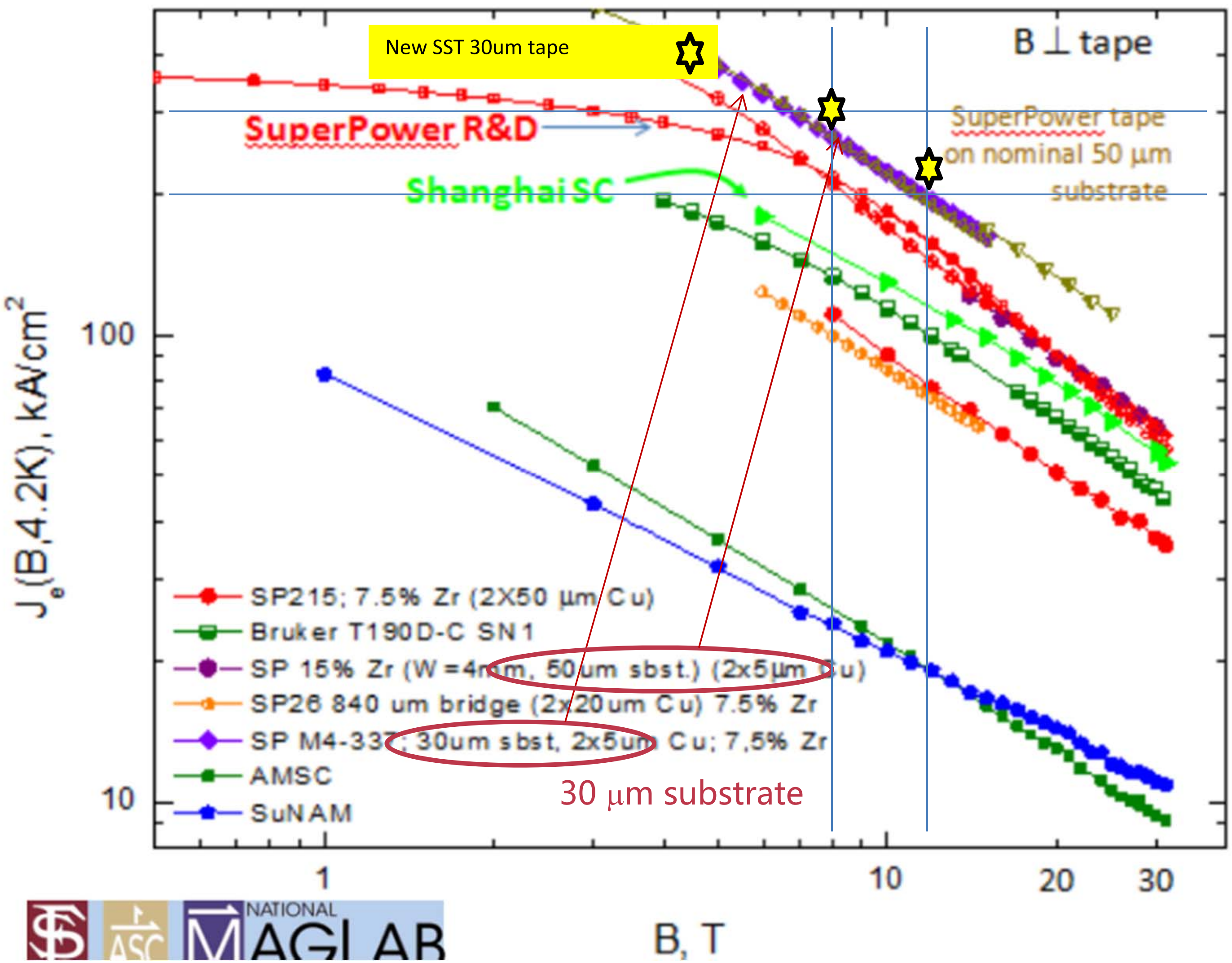


BHTS: highest layer J_C at 4.2 K in field

- Materials qualify through flux pinning mechanism for different temperature and field regimes
- Critical current at 4.2 K approx. one order of magnitude higher than at 77 K (self field)
- Substrate thickness of typically 60 - 100 microns is actually replaced by 30 - 50 micron for higher J_c^{eng} and improved bending
- Handling becomes more sophisticated !

Race for high engineering current densities goes on !

Shanghai Superconductor Technology competes now with leading manufactures (Y. Yamada, CEC-ICMC Hartford 2019)

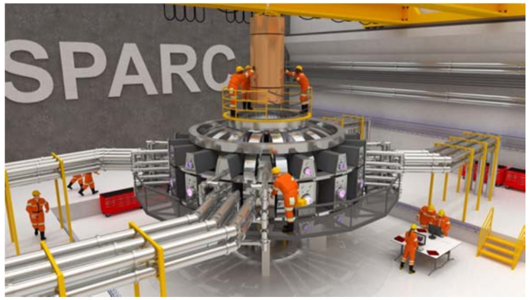


- **Reduced substrate tape thickness now reached 30 microns**
- **REBCO-CC are enabling materials for high magnet fields, providing:**
- **increased filling factors !**
- **Moderate current degradation in magnetic field**
- **Flexibility for amount of Cu stabilisation**

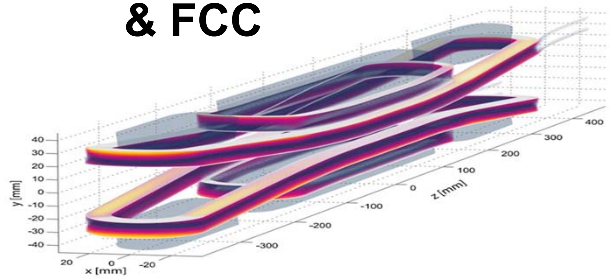
Motivation for developing HTS Magnets

- **Excellent current capacity at 4.2 – 30 K !**

- **Compact Fusion magnets (SPARC), the future ?**
- **Accelerator magnets FCC CERN**
- **MRI (high resolution, high field)**
- **NMR (1.2 GHz + spectrometer)**
- **Research magnets**
- **Magnets for heat treatment, separation, space etc..**



Hi-Lumi LHC & FCC

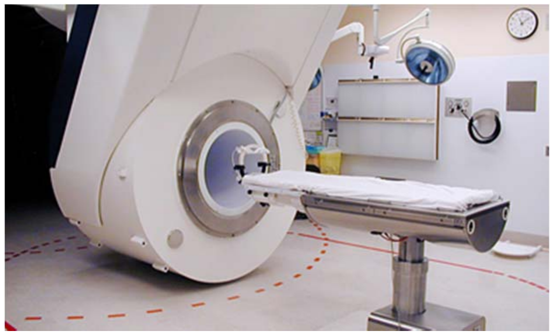


Magnet applications are drivers since HTS at 4.2 K is enabling technoly for higher fields (B >> 20 T)

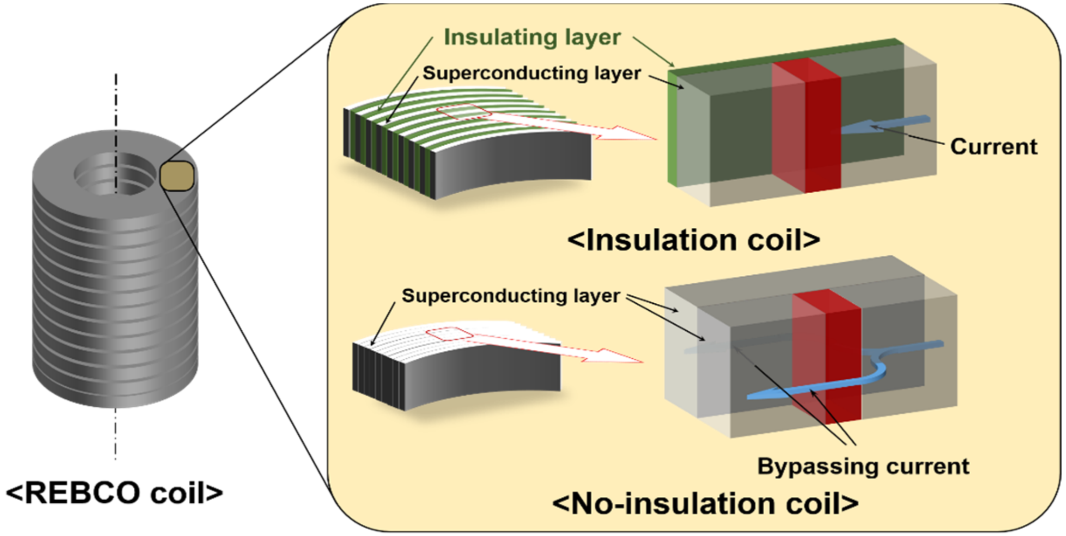
FCC (Future Circular Collider at CERN) can be most important driver and can become booster for all HTS applications

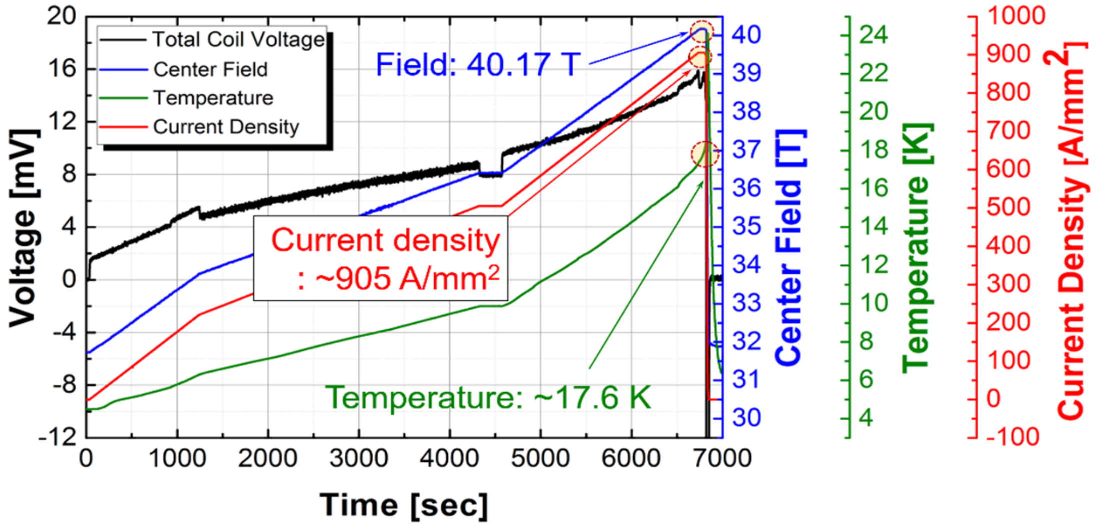
For NMR, MRI magnets persistent mode joints are needed, demonstrated already in lab !

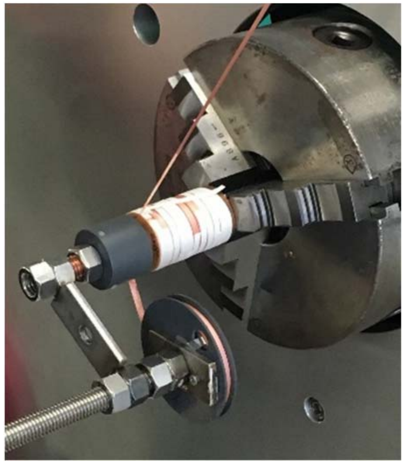
NMR & MRI

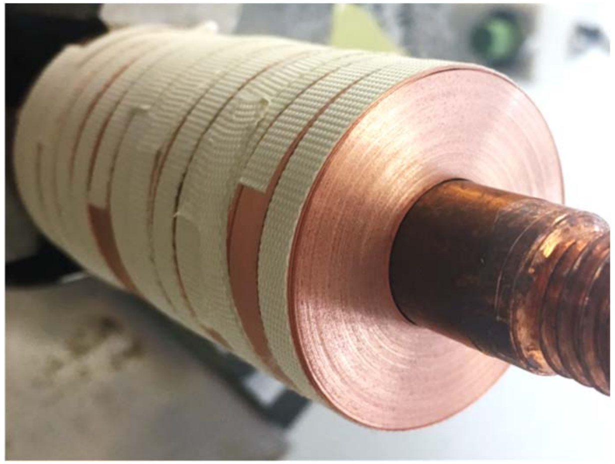


NI REBCO with SuperPower 30 μm substrate: 40 T!









- 240 m of 7.5Zr tape in 12 single pancakes (14 ID/34 OD/53mm long)
- Large helium bubble due to gas produced by joints
- Safe quench at 18 K
- Total field >40 T
- Test done April 7, data still under review

Hahn *et al.* : https://nationalmaglab.org/news-events/news/new-approach-to-building-magnets-yields-new-world-record

Development of a NI REBCO-HTS magnet (SMES appl. ?)

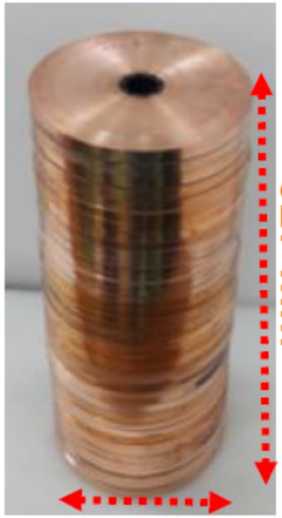
26.4 T all 2G wire one-body(non-nested) magnet

No-insulation, multi-width, and compact !

✓ Multi-width Double Pancake Coils

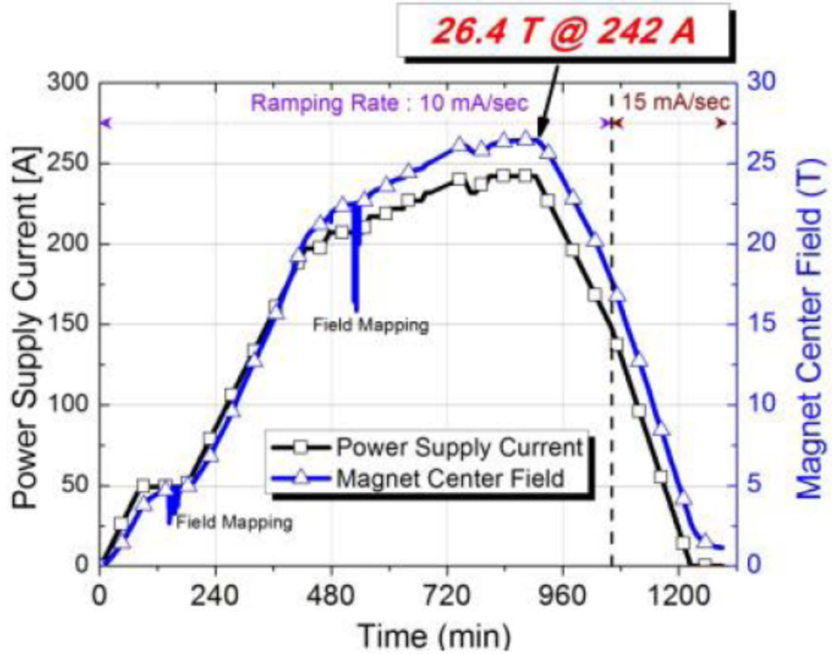
Potential 40 T with 30 micron substrate

✓ Stacked Double Pancake Coils



O.D. 172mm
I.D. 35mm

✓ Fully assembled



Immersed in liquid Helium

(Designed by S. Hahn (MIT→ NHMFL/FSU)

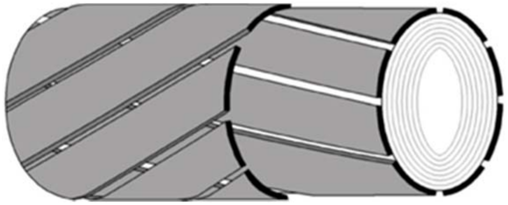
SUNAM

NATIONAL HIGH MAGNETIC FIELD LABORATORY

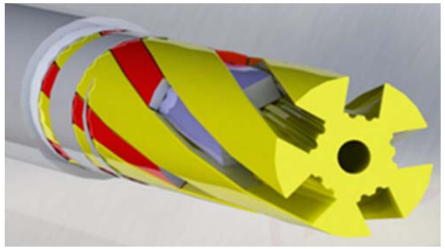
Large magnets require cables for high currents
Transposition of the strands is favorable / necessary

Cables from REBCO tapes

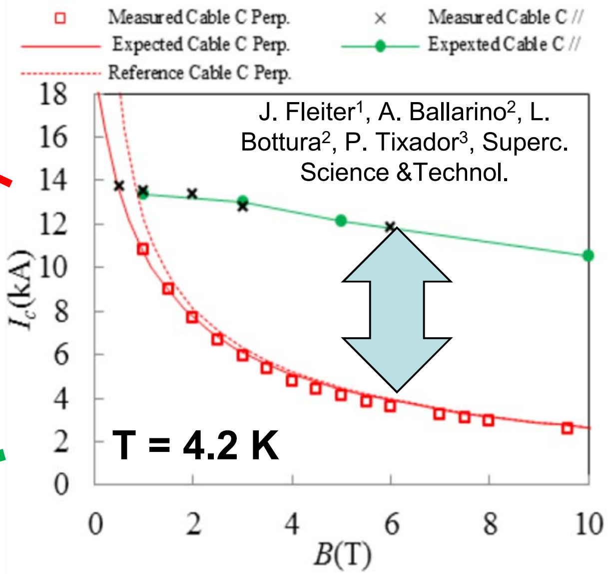
Roebel cable (KIT)

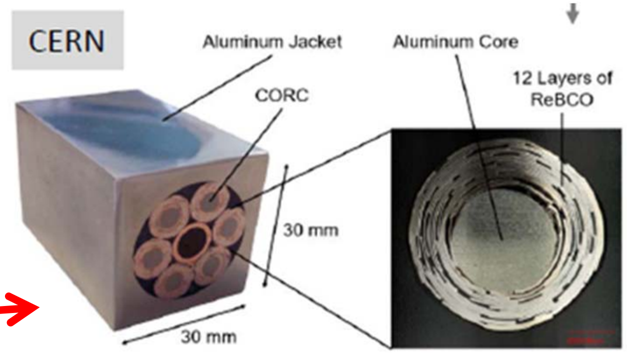


Conductor on round core (CORC, USA)

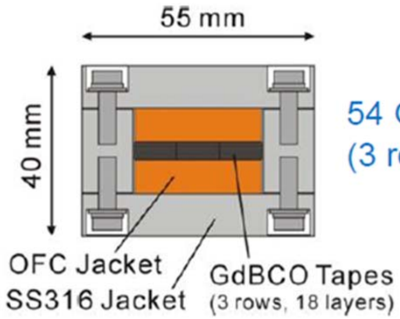


ENEA Tratos cable (ENEA, IT)



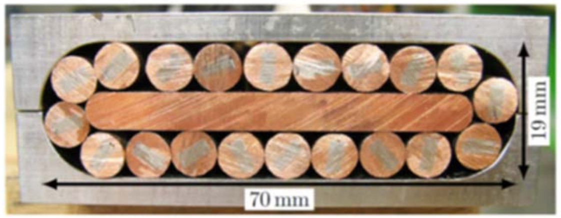


CORC in Conduit (CERN)

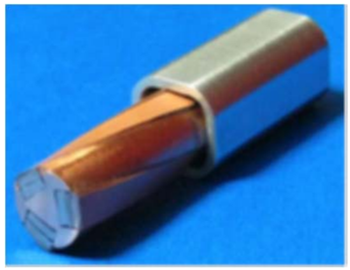


54 GdBCO tapes (3 rows, 18 layers)

HTS Stars conductor (NIFS Japan) for Fusion Magnets



Rutherford cable (EPFL CH)

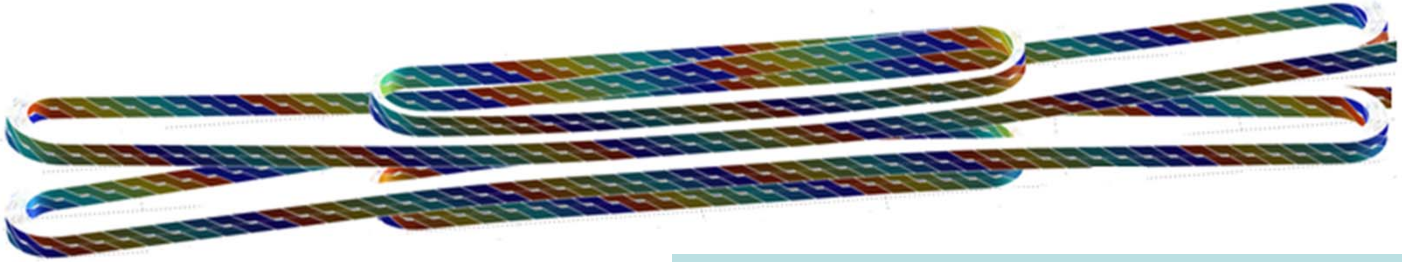


Twisted stacked tape cable, TSTC (MIT USA)

EU-project EUCARD2 (Future Magnets 2013-17)
WP10: dipole with 10-kA Class HTS Roebel cable

The dipole insert magnet design of CERN „Aligned block design“

The goal: 5 T dipole magnet for 4.2 K, 40 mm aperture
10 kA operation current at B = 20 T, length 0.5m
Cable length > 30 m

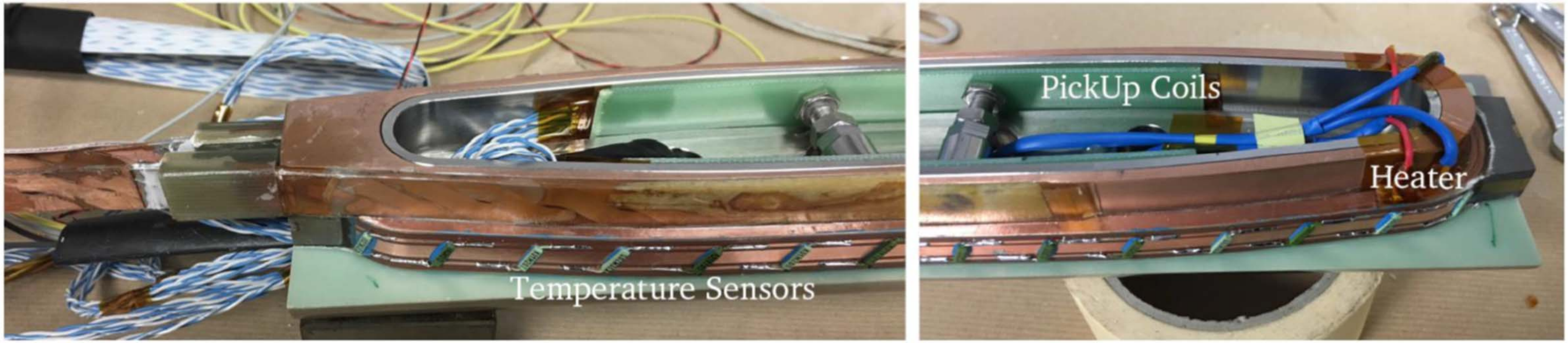


J van Nugteren et al, Powering of an HTS dipole insert-magnet operated standalone in helium gas between 5 and 85 K, Supercond. Sci. Technol. 31 (2018) 065002 (12pp)

Roebel cable provides excellent bending
Full transposition

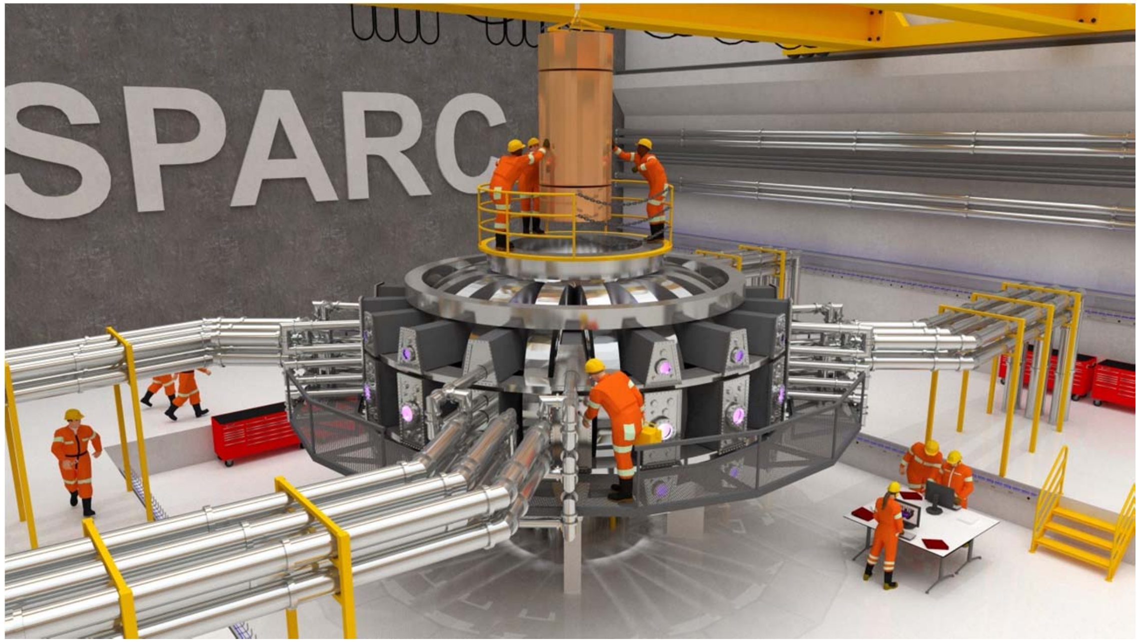
B = 3.35 T (10K) achieved in self field, tests are ongoing with improved cables in FRESCA test facility at CERN

Lead End | Turn End

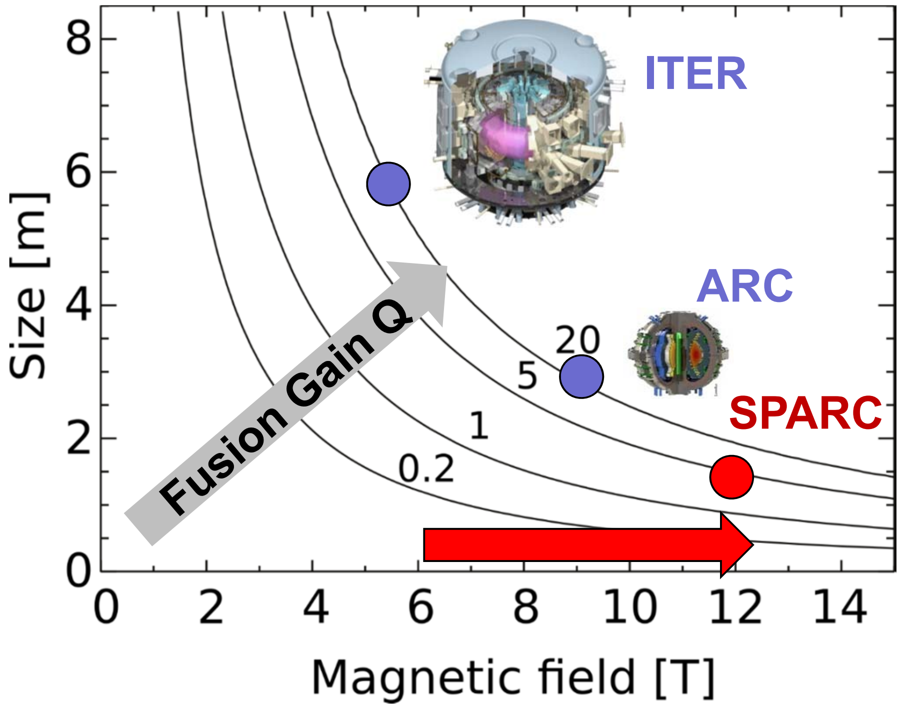


Coop. MIT(PSFC) – CFS
(Commonwealth Fusion Systems)

SPARC: A step on the high field path to Practical Fusion Energy



- Goal is to achieve break-even Fusion power of 500 MW
- HTS at 4.2 K allows very compact high field magnets and a compact machine design
- Consequence is favorable for first wall, no blanket necessary
- In a first step goal: demonstration of HTS magnet and prove of feasibility



➡ Field regime only accesible with HTS magnet technology

ARC: Pilot Plant Concept

Sorbom et al., Fusion Engineering and Design **100**, 378, 2015

Motivation for HTS in Energy Technology

Karlsruhe Institute of Technology

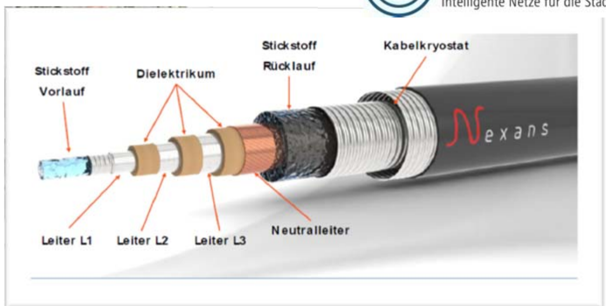
integration of renewable energy, a save new grid structure, efficient energy use, establishing a future environment friendly technology

- **Power cables** (HVDC, MVAC, HVAC)
- **Industry DC high power cables** (20-100 kA)
- **Fault current limiters** (resistive, inductive)
- **Self limiting HTS transformer** (MV/LV)
- **Wind energy generators** (AC and ? DC)
- **Electrical Airplane** (short range, emission-free)
- **SMES** (grid stabilisation)
- **Maglev** levitation trains **?**

Smartcoil FCL

ECO-swing

AMPACITY
Intelligente Netze für die Stadt



HTS Transformer KIT/ABB

HTS AC Energy Cables: change to REBCO

KIT Karlsruhe Institute of Technology

usually integration of fault current limiter in series

Manufacturer	Place ,Country, Year	Data	HTS
??	Chicago, Shanghai, ??		??
LS Cable	Seoul, Korea, 2017	22.9 kV, 1000 m	YBCO
Nexans	Essen, Deutschland, 2014	10 kV, 2.4 kA, 1000 m	BSCCO
Sumitomo	Yokohama, Japan, 2013	66 kV, 1.8 kA, 240 m	BSCCO
LS Cable	Icheon, Korea, 2011	22.9 kV, 3.0 kA, 100 m	BSCCO
LS Cable	Icheon, Korea, 2009	22.9 kV, 1.3 kA, 500 m	BSCCO
Nexans	Long Island, US, 2008	138 kV, 2.4 kA, 600 m	BSCCO/YBCO
LS Cable	Gochang, Korea, 2007	22.9 kV, 1.26 kA, 100 m	BSCCO
Sumitomo	Albany, US, 2006	34.5 kV, 800 A, 350 m	BSCCO
Ultera	Columbus, US, 2006	13.2 kV, 3 kA, 200 m	BSCCO
Sumitomo	Gochang, Korea, 2006	22.9 kV, 1.25 kA, 100 m	BSCCO
Furukawa	Yokosuka, Japan, 2004	77 kV, 1 kA, 500 m	BSCCO

Several successful field tests with voltages up to 138 kV and cable length up to 1000 m

Energy cable Essen City

AMPACITY
Smart grids for the city

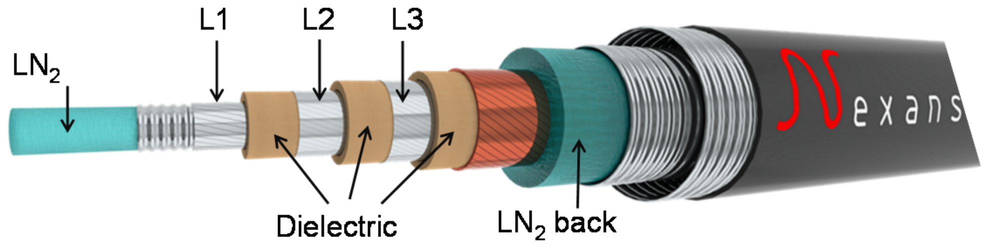
KIT Karlsruhe Institute of Technology

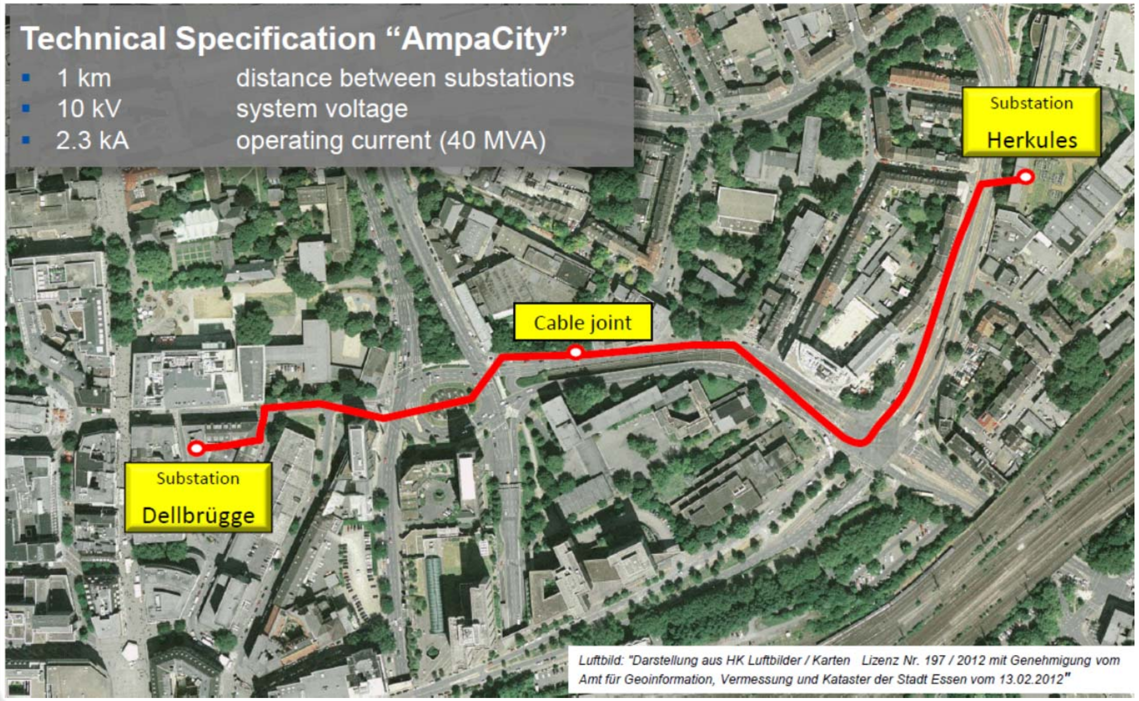
Supported by:
Federal Ministry of Economics and Technology
on the basis of a decision by the German Bundestag

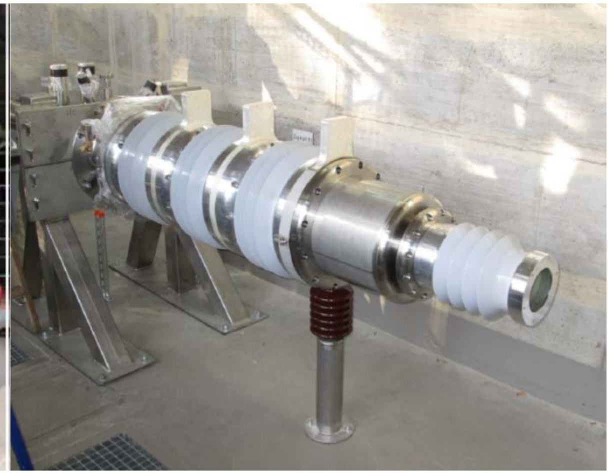
- Co-axial 3-phase cable
- 40 MVA, 10 kV, 1 km length, 1 splice
- BSCCO(2223) HTS, YBCO tested (KIT)
- Fault Current Limiter (serial)
- Operation extended.: 5 years failure free

Project partners (9/2011-2/2016)

innogy, Nexans, KIT Karlsruhe Institute of Technology, PtJ Projektträger Jülich Forschungszentrum Jülich







FCL Terminations 3 - phase

HTS Cables – Ampacity Cooling System

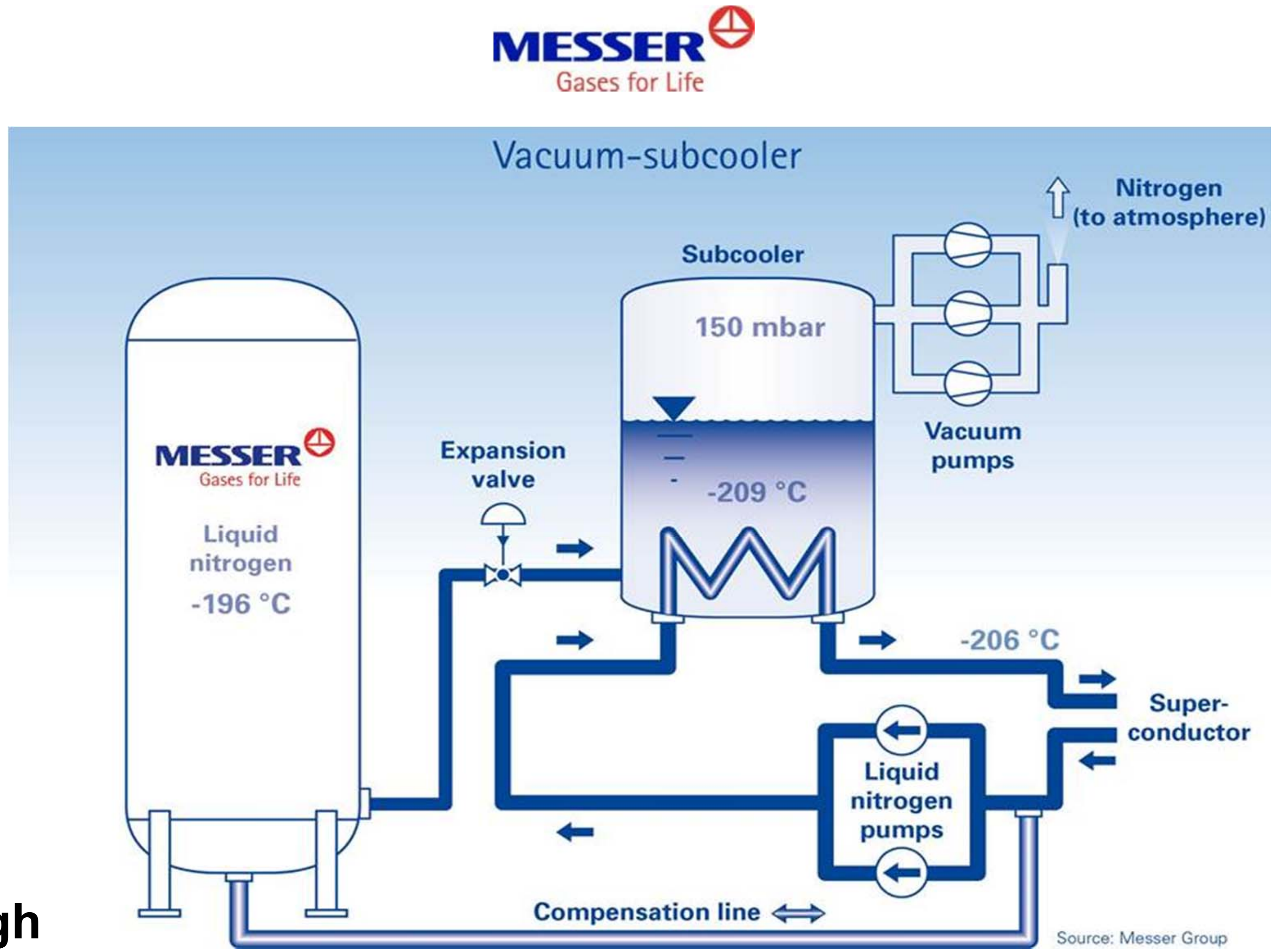
Liquid nitrogen is used
- as heat transfer medium
- as cooling agent

LN_2 is pumped through the superconducting cable

LN_2 is recooled in the subcooler (to -206°C)

LN_2 vaporizes at 150 mbar(a) (forced by vacuum pumps)

LN_2 temperature decreases to -209°C (expansion through the regulation valve)



Source: F. Herzog, et.al. , „Cooling unit for the AmpaCity project – One year successful operation", Cryogenics Volume 80, Part 2, December 2016, Pages 204-20, DOI: 10.1016/j.cryogenics.2016.04.001

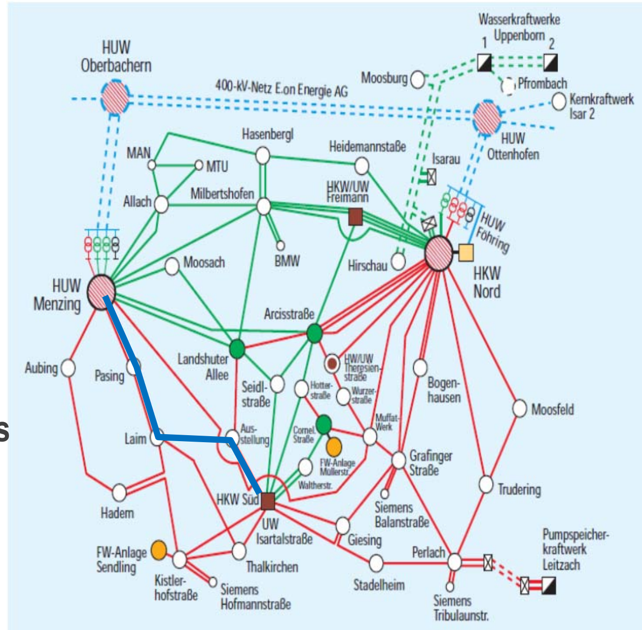
Possibly next quantum step for HTS energy cables

W. Prusseit EUCAS 2019

SUPERLINK – 500 MVA HTS CABLE BACKBONE

SuperLink project: development of components for 12 km long, 110 kV HTS cable (500 MW)

- Development of a compact 110 kV HTS cable
- Detailed concept for 12 km long cable route
- Design of efficient cryo-cooling system
  - Efficient TB cooler
  - Slim cable cryostat
  - Intermediate pumping & cooling stations
- Demo of 100 m cable and all components in Munich grid substation
- Start expected early 2020



Favorable business case
HTS cable beats conventional solutions

Consortium

Utility	SWM
Cable	NKT
Cryogenics	THE LINDE GROUP
HTS wire	THEVA
Instituts	KIT Karlsruhe Institute of Technology; Fachhochschule Südwestfalen University of Applied Sciences

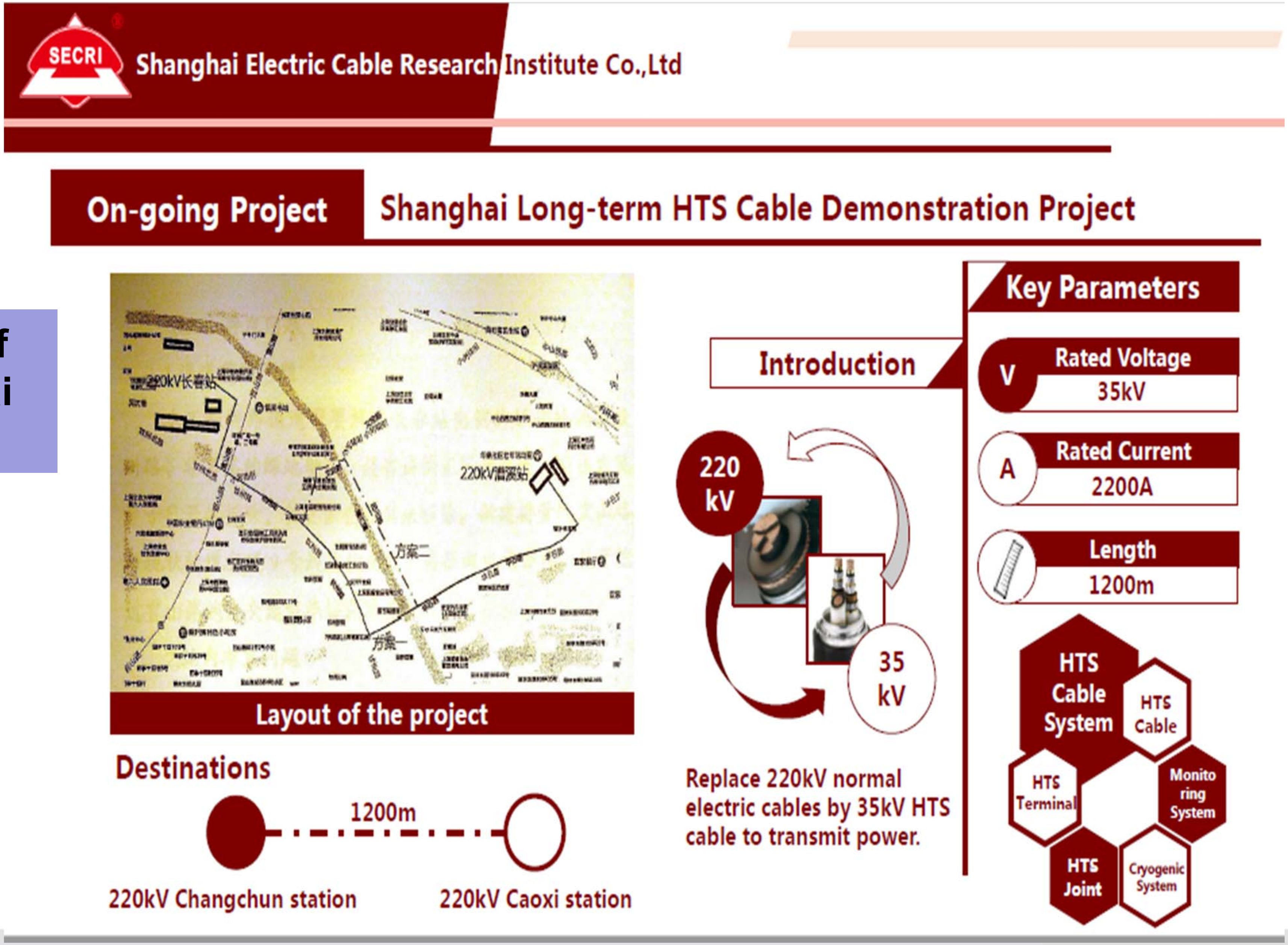
After successful demo Munich city utility wants to realize the 12 km HTS cable

New Project of HTS cable in Shanghai

上海电缆研究所
Shanghai Electric Cable Research Institute

Y. Yamada, CEC-ICMC conference Hartford 2019

Center of Shanghai City



New Project of HTS cable in Shanghai

上海电缆研究所 Shanghai Electric Cable Research Institute

Y. Yamada, CEC-ICMC conference Hartford 2019

SECRI Shanghai Electric Cable Research Institute Co.,Ltd

On-going Project | Shanghai Long-term HTS Cable Demonstration Project

Besides,

- 10kV/2kA HTS DC transmission demonstration project(Shenzhen) and
- HTS cable demonstration project(Zhongshan) are going to start soon.

220kV Changchun station 220kV Caoxi station Joint System

Modular HTS-DC High Current Bar: project 3S

Supported by: Federal Ministry of Economics and Technology on the basis of a decision by the German Bundestag

KIT Karlsruhe Institute of Technology

VISION ELECTRIC Super Conductors

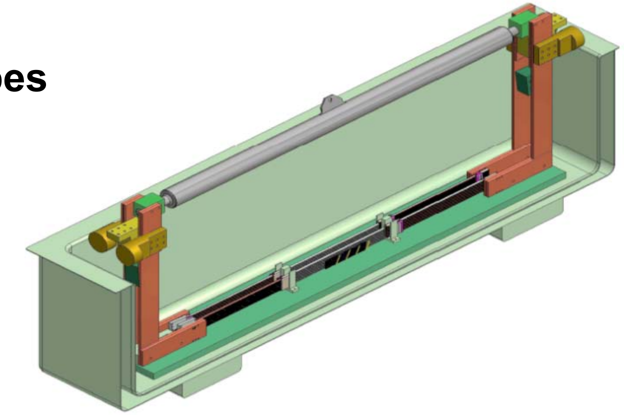
ILK Dresden

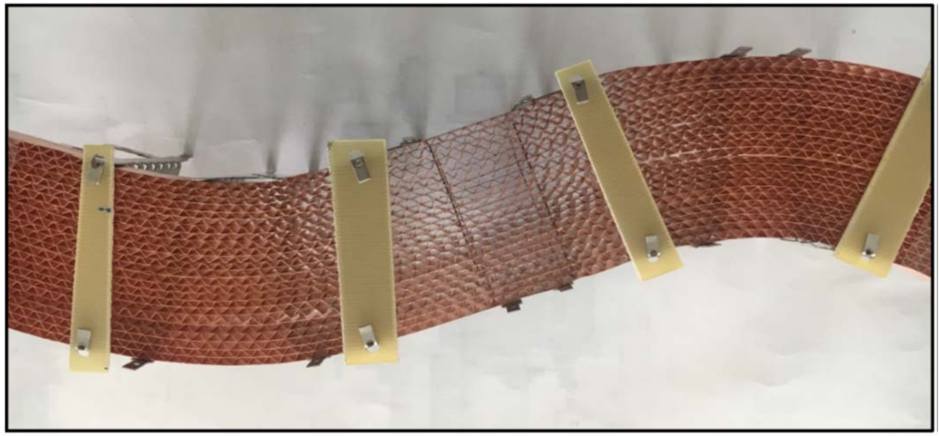
KIT Karlsruhe Institute of Technology

- **20 kA DC, 25 m**
- **Test of 2 m subscale 10 kA**
- **25m in 7 segments produced**
- **Low loss current leads developed**
- **Joint technology developed**
- **Field test still under way (BASF)**

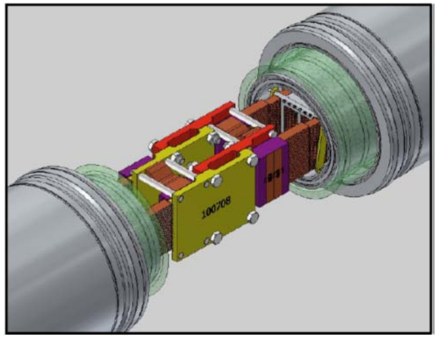
Applications	Current	Length
NaCl-electrolysis	20 kA	30-300 m
Data Centers	15-40 kA	40-200 m
Cu-electrolysis	40-80 kA	200-400 m
Al-smelters	Up to 500 kA	100-500 m

Subscale:
2 x 23 stacked tapes
10 kA nominal
3 segments 0.7 m
2 joints
IN2 bath croystat





Cable **joint**



Cooling:
Circulated LN2 with pump

Ref. S.Elschner et al. EUCAS-2017, Geneva, 3L04-07

Fault Current Limiters (FCL)

- **Field test experience of resistive type superconducting FCL**
- **Trend: FCL function integrated in devices (Trafo, cable etc,)**
- **Long term field test, demand and market still missing**

Lead Company	Year/Country	Data	Superconductor
ACCEL/NexansSC	D / 2004	12 kV, 600 A	Bi 2212 bulk
Nexans SC	D / 2009	12 kV, 100 A	Bi 2212 bulk
Nexans SC	D / 2009	12 kV, 800 A	Bi 2212 bulk
RSE	I / 2011	9 kV, 250 A	Bi 2223 tape
RSE	I / 2012	9 kV, 1 kA	YBCO tape
KEPRI	Korea / 2011	22.9 kV, 3 kA	YBCO tape
Nexans SC	D / 2011	12 kV, 800 A	YBCO tape
Nexans SC	D / 2013	10 kV, 2.4 kA	YBCO tape
Applied Materials	US /2013	15 kV / 1kA	YBCO tape
Nexans SC	UK /2015	12 kV, 1.6 kA	YBCO tape
Siemens	D / 2016	12 kV, 815 A	YBCO tape
SuperOx	Russia/2019	220 kV, 1 kA	YBCO tape

More than 10 successful field tests of resistive type superconducting fault current limiters at medium voltage level since 2004

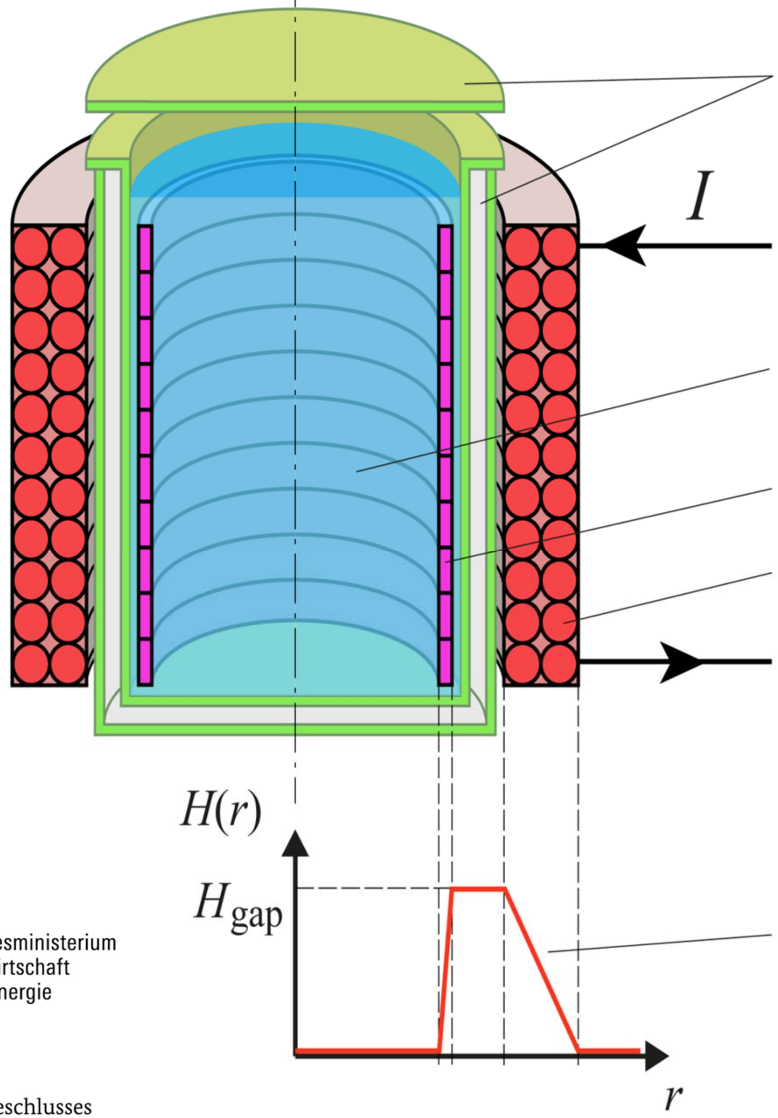
SmartCoil – inductive current limiter

Stacked modules, module design verified by successfull test

SIEMENS
ILK Dresden
KIT - ITEP

KIT Karlsruhe Institute of Technology

600 A , 10 kV „air-coil“ supercond. - FCL



- Nominal voltage U_{nom} 5.77 kV_{RMS}
- Current limiting time 100 msec
- 80 short-cut 2G HTS-rings (D = 1.2 m)
- Soldered low resistance contacts
- CC customized by Cu – layer thickness

Gefördert durch:

Bundesministerium für Wirtschaft und Energie

aufgrund eines Beschlusses des Deutschen Bundestages

SuperOx (Russia): Production of REBCO tapes and development of applications: Fault Current Limiter

A. Molodyk, CEC-ICMC Hartford 2019

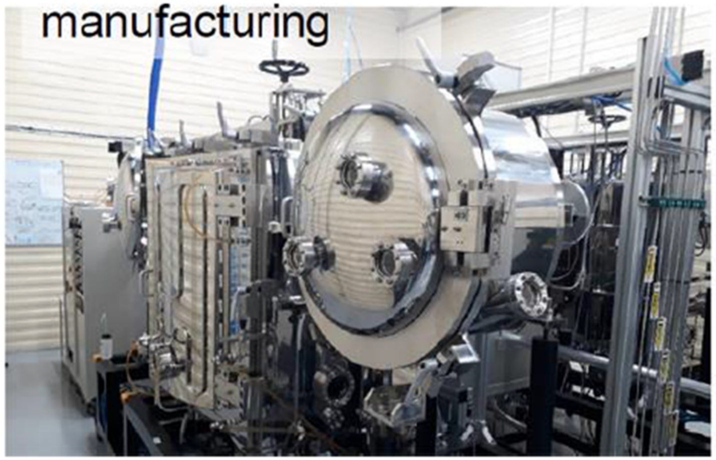
HTS applications: 220kV / 450 MW FCL for Moscow city grid

SuperOx

- First FCL in Russian Power Grid
- 220 kV-class
- In operation 2019
- SuperOx manages entire project

2. Engineering and production

1. Superconductor manufacturing



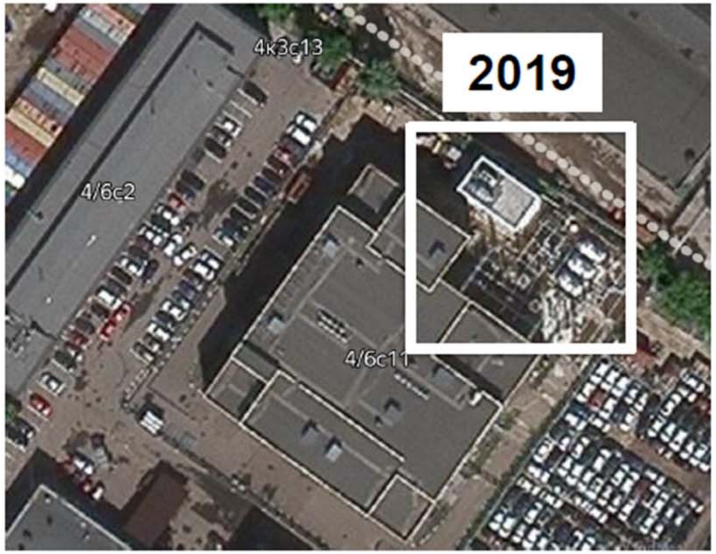
3. Onsite construction

Pictures from FCL grid implementation

A. Molodyk, CEC-ICMC Hartford 2019

220kV / 450 MW FCL: pilot operation in grid since June 2019

SuperOx



Fault Current Limiter using SST Tapes

Y. Yamada CEC-ICMC Hartford 2019

KIT Karlsruhe Institute of Technology

High voltage HTS FCL

- Zhongtian Technology
- Project: HTS FCL
- "220 kV resistive HTS FCL" was checked and accepted at the end of 2017.

Most recent one

- Southern Electric Power Research Institute
- Project: HTS FCL
- "500 kV large inductive FCL prototype".
- "160 kV DC resistive FCL prototype"


220kV HTS FCL

500kV large inducive FCL

160kV DC resistive FCL

Transformer

Stagnating activities, long term field test is missing, integrated FCL function demonstrated

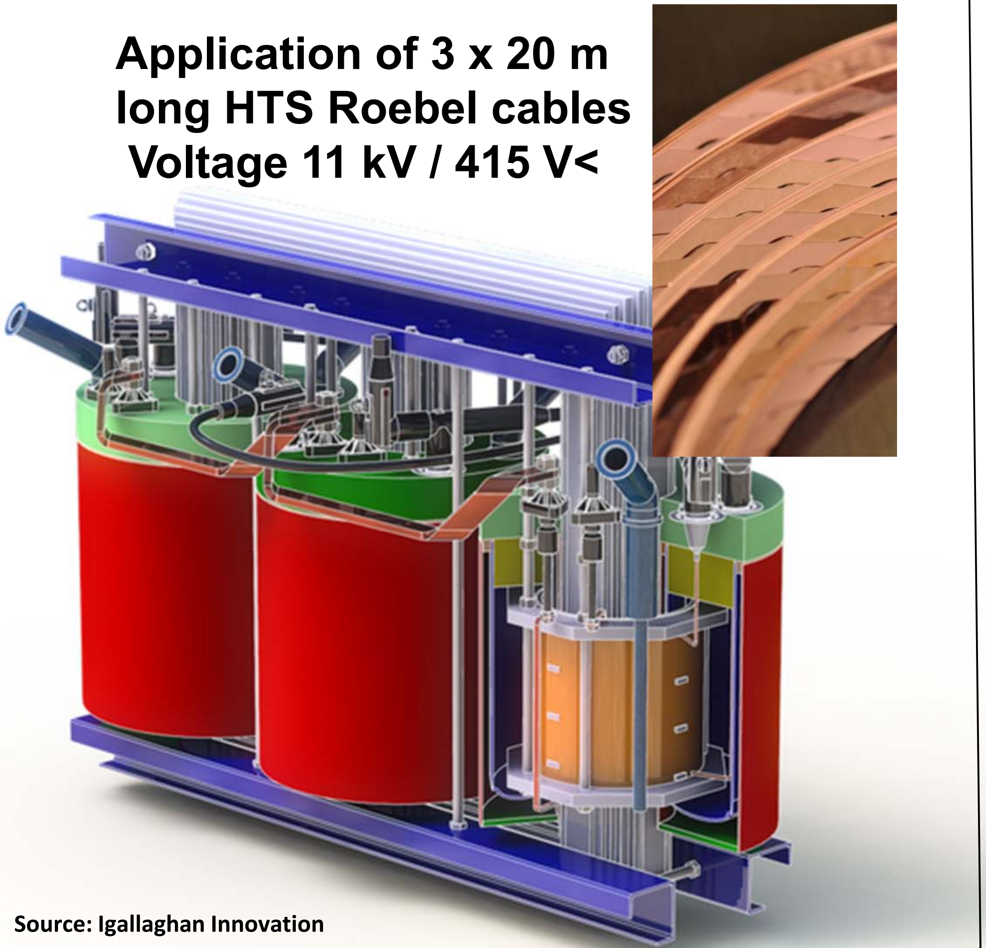
Country	Inst.	Application	Data	Phase	Year	HTS
Switzerland	ABB	Distribution	630 kVA, 18,42 kV/420V	3 Dyn11	1996	Bi 2223
Japan	Fuji Electric	Demonstrator	500 kVA, 6,6 kV/3,3 kV	1	1998	Bi 2223
Germany	Siemens	Demonstrator	100 kVA, 5,5 kV/1,1 kV	1	1999	Bi 2223
USA	Waukesha	Demonstrator	1 MVA, 13,8 kV/6,9 kV	1	-	Bi 2223
USA	Waukesha	Demonstrator	5 MVA, 24,9 kV/4,2 kV	3 Dy	-	Bi 2223
Japan	Fuji Electric	Demonstrator	1 MVA, 22 kV/6,9 kV	1	2001	Bi 2223
Germany	Siemens	Railway	1 MVA, 25 kV/1,4 kV	1	2001	Bi 2223
EU	CNRS	Demonstrator	41 kVA, 2050 V/410 V	1	2003	P-YBCO/S-Bi 2223
Korea	U Seoul	Demonstrator	1 MVA, 22,9 kV/6,6 kV	1	2004	Bi 2223
Japan	Fuji Electric	Railway	4 MVA, 25 kV/1.2 kV	1	2004	Bi 2223
Japan	Kuyshu Uni.	Demonstrator	2 MVA, 66 kV/6.9 kV	1	2004	Bi 2223
China	IEE CAS	Demonstrator	630 kVA, 10.5 kV/400 V	3	2005	Bi 2223
Japan	U Nagoya	Demonstrator	2 MVA, 22 kV/6,6 kV	1	2009	P-Bi 2223/S-YBCO
Japan	Kyushu Uni	Demonstrator	400 kVA, 6.9 kV/2.3 kV	1	2010	YBCO
Germany	KIT	Demonstrator	60 kVA, 1 kV/600 V	1	2010	P-Cu/S-YBCO
USA	Waukesha	Prototype	28 MVA, 69 kV	3	Not completed	YBCO
Australia	Callaghan Innovation	Demonstrator	1 MVA, 11 kV/415 V	3 Dy	2013	YBCO
China	IEE CAS	Demonstrator	1.25 MVA, 10.5 kV/400 V	3 Yyn0	2014	Bi 2223
Germany	KIT/ABB	Demonstrator	577 kVA, 20 kV/1 kV	1	2015	P-Cu/S-YBCO

HTS Transformers

Development of a three phase 1 MVA HTS Transformer 2013

Gallaghan Innovation, Wilson Transf., General Cable

Application of 3 x 20 m long HTS Roebel cables Voltage 11 kV / 415 V<



Source: Igallaghan Innovation

More information: Neil D. Glasson, Mike P. Staines, Zhenan Jiang, and Nathan S. Allpress, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013

1 MVA HTS Transformer with recovery under load function

- Primary winding: 20 kV_{RMS} / 28.87 A_{RMS} (warm, copper)
- **Secondary** winding: 1 kV_{RMS} / 577.35 A_{RMS} (2G HTS)

KIT + ABB

PhD thesis S.Hellmann download at: https://publikationen.bibliothek.kit.edu/1000088555

State of the Art of HTS rotating machines

Karlsruhe Institute of Technology

- **Machines with a rating of up to 36 MVA were built and tested**
- **New application fields as airplanes are under investigation**

Manufacturer / Country	Machine	Timeline
AMSC (US)	5 MW demo-motor	2004
	8 MVA, 12 MVA synchronous condenser	2005/2006 (**Field test**)
	36 MW ship propulsion motor	2008
GE (US)	5 MVA homopolar induction motor	2008
LEI (US)	5 MVA high speed generator	2006
Kawasaki (JP)	1 MW ship propulsion	200?
IHI Marine, SEI (JP)	2.5MW ship propulsion motor	2010
Doosan, KERI (Korea)	1 MVA demo-generator	2007
	5 MW motor ship propulsion	2011
Siemens (Germany)	4 MVA industrial generator	2008 (**Field test**)
	4 MW ship propulsion motor	2010
Converteam (UK)	1.25 MVA hydro-generator	2010
Ecoswing (EU)	3 MW wind generator	2018 (Field test)

So far three field test of more than a MW superconducting machines were reported

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LEI (US)	[illegible]	[illegible]
Kawasaki (JP)	[illegible]	[illegible]
IHI Marine, SEI (J	[illegible]	[illegible]
Doosan, KERI (K	[illegible]	[illegible]
	[illegible]	[illegible]
Siemens (Germany)	4 MVA industrial generator	2008 (**Field test**)
	4 MW ship propulsion motor	2010
Converteam (UK)	1.25 MVA hydro-generator	2010
Ecoswing (EU)	3 MW wind generator	2018 (Field test)

Important Innovation !
Closed cooling system with liquid Neon at 28 K and refrigerator

So far three field test of more than a MW superconducting machines were reported

Ecoswing the world`s first HTS wind energy generator and machine

- 3.6 MW (2.8 MW achieved), 15 rpm, 128m rotor
- Reduction of weight 40%, diameter 5.4 to 4m
- Field test successfull for already 169 hrs.
- Installed at : Thyborøn, Denmark ENVISION

ecoswing

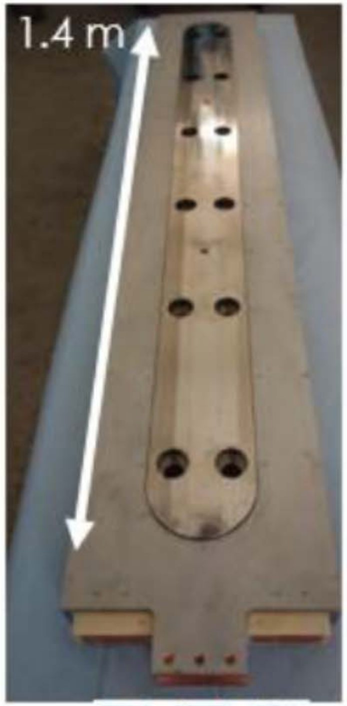
Horizon 2020
European Union Funding
for Research & Innovation

ENVISION, ECO, JEUMONT, DELTA, THEVA, SHI, Fraunhofer, UNIVERSITY OF TWENTE., DNV·GL

KIT Karlsruhe Institute of Technology

Objective: retrofitting of the classical generator

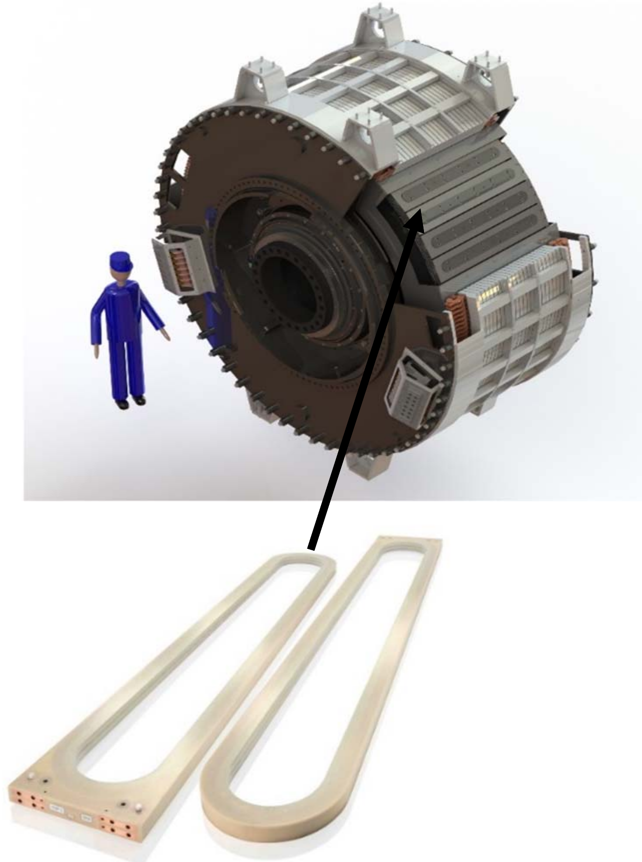
Ecoswing, HTS coils from Theva ReBCO-tape



THEVA

JEUMONT Electric

UNIVERSITY OF TWENTE.



- Appr. 25 km HTS tape used
- 43 race track coils manufactured and tested with length of 1.4 m

Cooling technology:
Cryocooler with cold head and compressor in the nacelle (more in next talk)

Project costs 14 M€, but a very promising step towards new power dimension !

HTS application in electrical emission free airplanes

Karlsruhe Institute of Technology

HTS applications: HTS motor for aircraft. Horizon 2020 consortium.

SuperOx

HORIZON 2020

ASuMED

Funded by the European Commission Grant No 723119

Supported by Grant 075-11-2018-176
Ministry of Science and Higher Education of Russia

Advanced Superconducting Motor Experimental Demonstrator

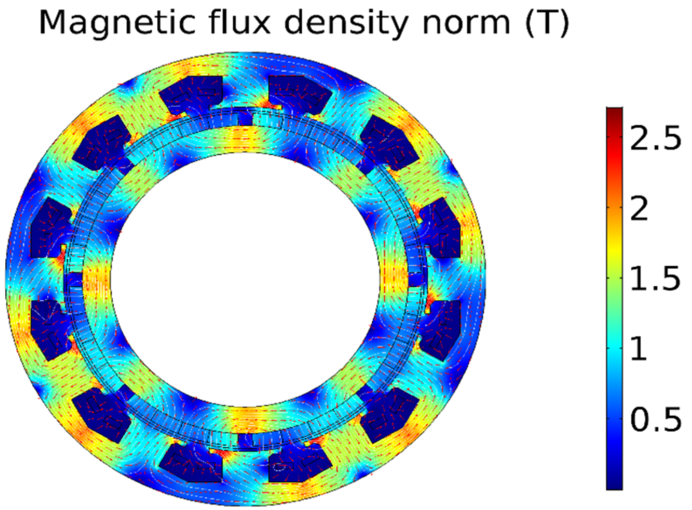
Source: Airbus Group Innovations

C3Or2A-06
DEMACO: rotor cooling

OSWALD · UNIVERSITY OF CAMBRIDGE · AIR LIQUIDE · KIT Karlsruhe Institute of Technology · Rolls-Royce · DEMACO · SuperOx · hochschule aschaffenburg university of applied sciences · K·S · ELÚ

The ASUMED Project

- Advanced Superconducting Motor Experimental Demonstrator
- **Fully superconducting machine**
  - Stator: HTS coils **(4 times stronger than conventional)**
  - Rotor: HTS tape stacks as permanent magnets
- **Power density 20 kW/kg**
- **Prototype:**
  - ~1 MW power at 10,000 rpm
  - Thermal loss <0.1%
- **http://asumed.oswald.de/**



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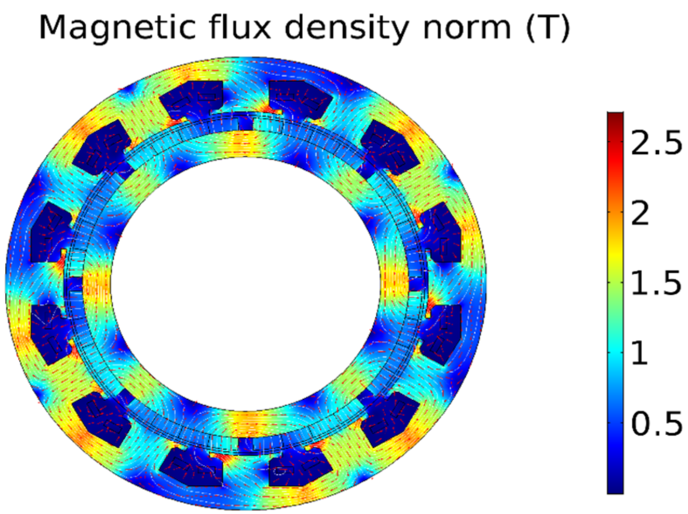


Numerical modeling will allow the first detailed AC loss evaluation in a fully superconducting machine

TELOS - Thermo-Electrically Optimised Aircraft Propulsion Systems

ends 12/2019

S.Schlachter CEC-ICMC Hartford 2019

SIEMENS KIT AIRBUS TUM Neue Materialien Bayreuth

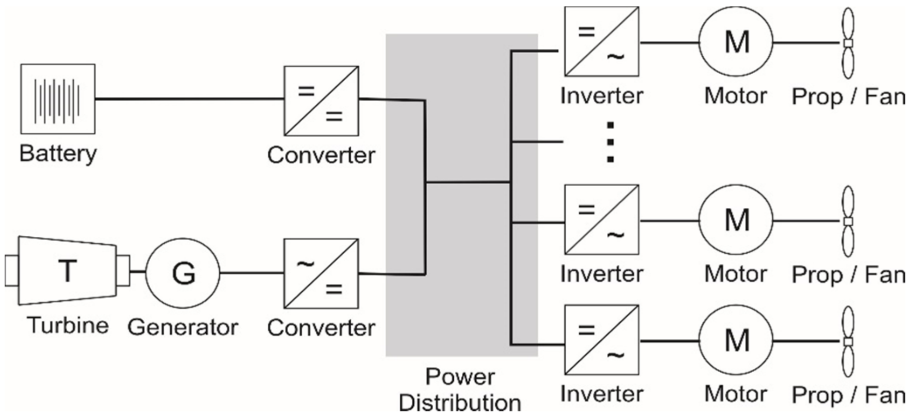
KIT Karlsruhe Institute of Technology

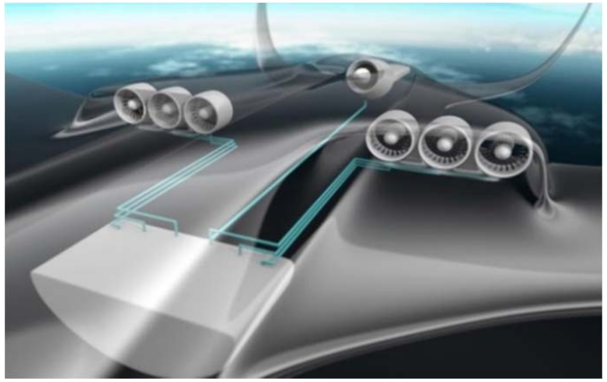
Supported by: Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag

Hybrid- electric propulsion systems

Purely electric propulsion not feasible for larger aircraft due to high battery weight

→ Hybrid-electric propulsion with battery and gas power unit
→ Thrust generation decentralized → design space for aircraft





http://img.welt.de/img/wirtschaft/crop127296741/4926936553-ci3x2l-w900/E-Thrust-2-.jpg

For aviation components with high power-to-weight ratio are required (e.g. motors, generators, cable systems, …)

➢ ***Superconductivity is the enabling technology for the high-power class***

Whole talk available: sonja.schlachter@kit.edu

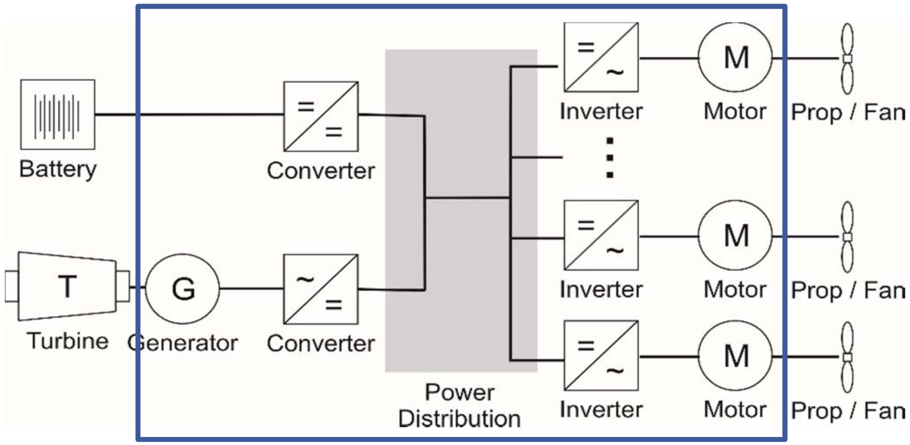
Cooling Options for DC Systems

S.Schlachter CEC-ICMC Hartford 2019

Karlsruhe Institute of Technology

Superconducting components: generator, cables, motor

- Option 1: <u>cryo electronics and combined cooling system </u>for all s.c. components



  - No current leads / strongly reduced low end temperature
  - **Cryo electronics required** (operation point far below RT)

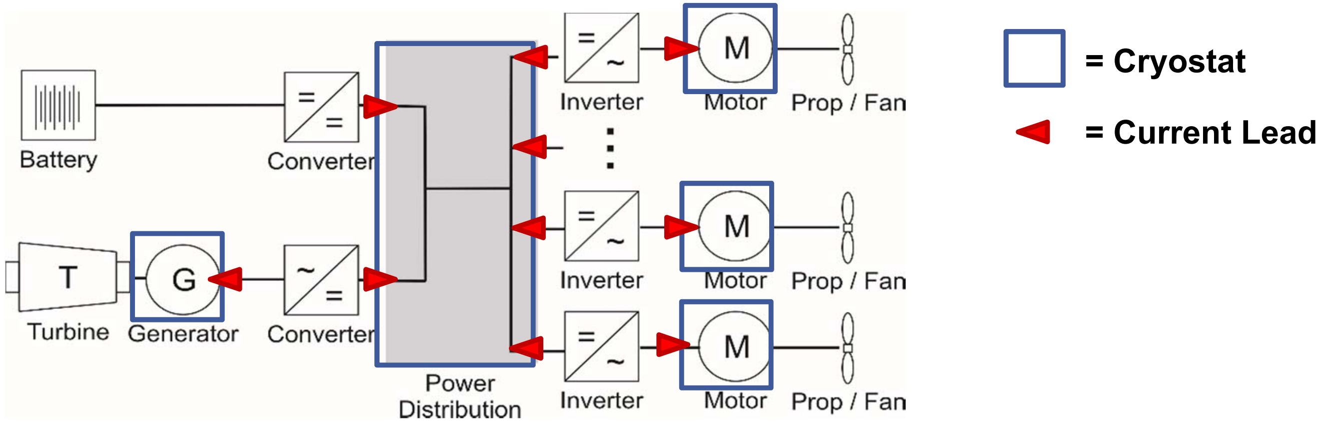
Whole talk available: sonja.schlachter@kit.edu

TELOS Cooling Options for DC Systems

S.Schlachter CEC-ICMC Hartford 2019

Superconducting components: generator, cables, motor

- Option 2: warm converters and separate cooling system for each s.c. component



- Optimized cooling system for each component → **High weight**
- **Many current leads required**

Payload is the big problem, lH_2 cooling is discussed, hydrogen not yet accepted, no power electronic for cryo-regime

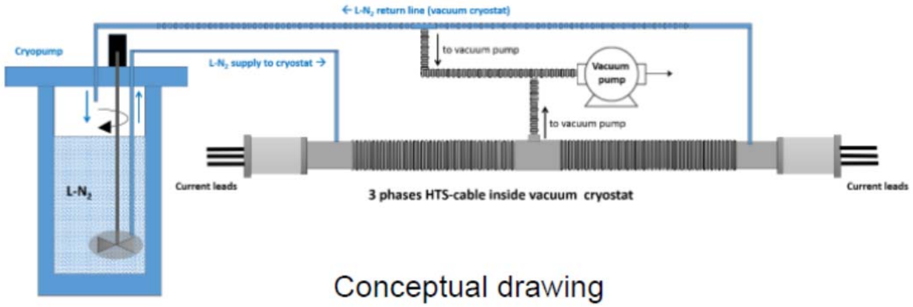
Whole talk available: sonja.schlachter@kit.edu

Contributions to Airbus goal „superconducting e-plane“

Cooperation of Airbus - SuperOx

12 MW AC cable system

Voltage	0...6000 V
Current	0...2000 A (peak)
Frequency	0...400 Hz
Short circuit test	12 kA



Conceptual drawing

Figs. SuperOx

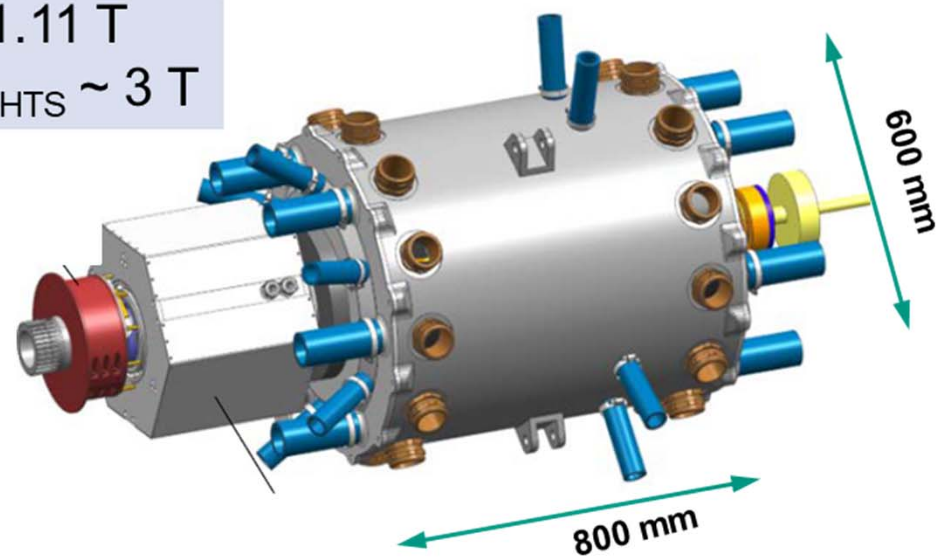
An Evaluation of Superconducting Power Cables for Airborne Application
2018 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), https://doi.org/10.2514/6.2018-5029

Result from a cooperation of Airbus - Siemens

Example Generator for E-Aircraft Study

10 MW | 7000 rpm | **21 kW/kg** | > 98 %, 476 kg

$B = 1.11$ T
$B_{max\ HTS} \sim 3$ T

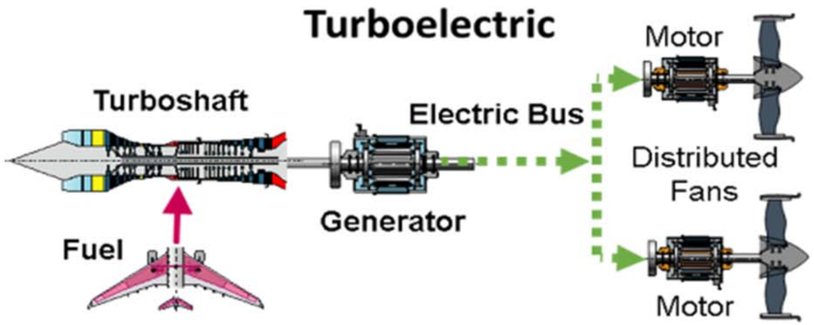


Data and picture: L. Kühn, et.al. High Power Density 10 MW HTS-Generator for eAircraft, EUCAS 2019, Glasgow

USA activities for Future Airplanes with HTS: NASA, Boing and Airforce (T. Haugn)

Karlsruhe Institute of Technology

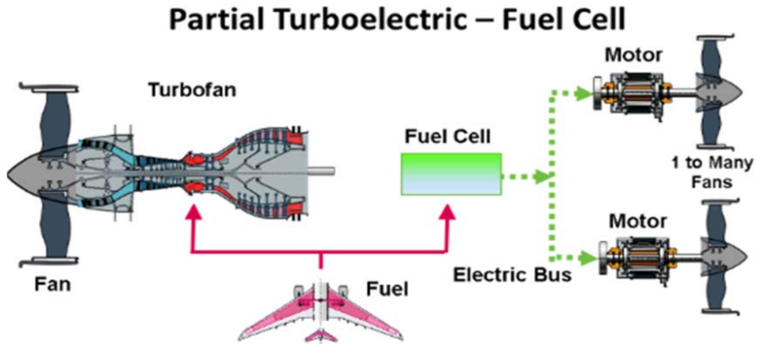
NASA-N3X



Fuel burn reduction 70%, same range, speed, airport infrastructure. Technology: Hybrid Wing Body, Fully distributed 50MW, Superconducting, 7500V, power system

Use of IH_2 fuel (=coolant) considered in the concepts

Boing SUGAR Freeze



fuel burn reduction 56% for 900 mile mission, utilizes a truss-braced wing combined with a boundary-layer ingesting fan in an aft tail cone to maximize aerodynamic efficiency. The aft fan is powered by a solid oxide fuel cell topping cycle and driven by a superconducting motor with a cryogenic power management system.

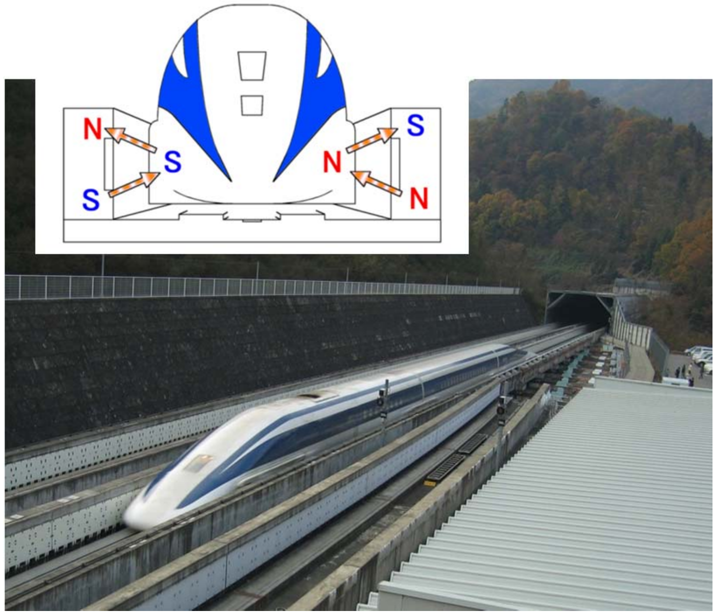
R&D on Cryo-power electronic !

Refs. and further reading

https://www1.grc.nasa.gov/aeronautics/hep/airplane-concepts/
https://www1.grc.nasa.gov/aeronautics/electrified-aircraft-propulsion-eap/eap-for-larger-aircraft/
https://www1.grc.nasa.gov/aeronautics/electrified-aircraft-propulsion-eap/

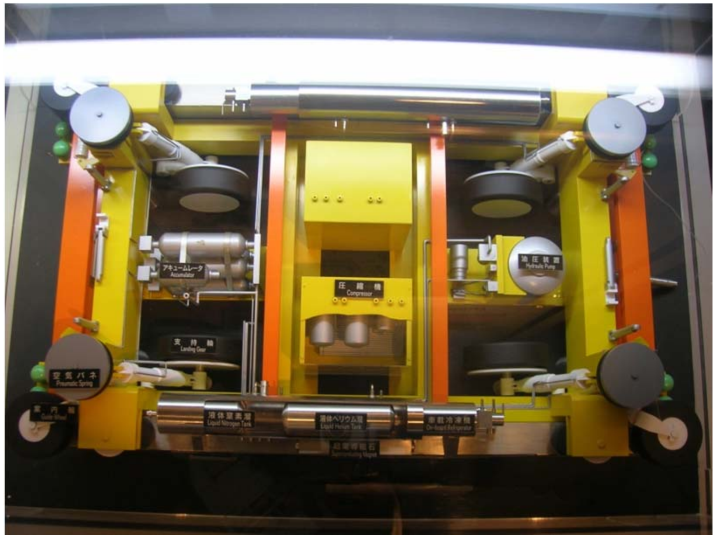
Mobility: High Speed Maglev Levitation Trains

- **JR (Japan) train: Record speed of 603 km/h**
- **Track Tokyo – Nagoya - Osaka under work**
- **Operation planned for 2027**
- **Inductively excited SC magnets on train**



Other levitation trains planned

- **China: Bejing-Shanghai 373 mph, production 2021, China Railway Rolling Stock Corp. (CRRC)**
- **USA: Washington – NY City, Japanese system**



NbTi magnets used in train ! Why not HTS ?

- **Persistent mode joints in HTS not standard !**
- **HTS would also need operation at lHe for high currents and high fields**
- **NbTi = stabilized, robust, cheap, reliable, approved as persistent mode coils**

Summary

- HTS are essential for compact magnets and enable advanced high field magnets (operated at 4.2 K)
- Persistent mode joints were successfully demonstraded, routine application still missing (NMR, Maglev levitation magnets, etc.…)
- HTS power cables show slow progress (FCL integrated), are in field
- Rotating machinery, transformer: missing long term field tests
- Fault current limiters (standalone) FCL still fighting for market
- Cooling technology established, approved, availlable (good news)

Limitations from Coated Conductor:

- Unsufficient homogeneity and stability (delamination, hot spots)
- CC prize level still too high and quite stable
- Real mass production missing, impact on prize will be moderate !

⇨ HTS competes in energy sector against long term investments (> 30 years), negligible maintenance, approved long term performance !

Acknowledgement

Contributions and provided presentations are highly acknowledged (were a big help) from:

Tim Haugn, V. Mathias, H. tenKate, A. Kario, G. Kirby, D. Larbalestier, S Otten, M. Marchevsky, A. Molodyk, M. Bauer, W. Prusseit, S. Schlachter, Y. Yamada, A. Kudymow, S. Elschner, L. Kühn, A. Kudymow

Thank you for your interest !